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TRITIUM MANAGEMENT IN FUSION REACTORS

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TRITIUM MANAGEMENT IN FUSION REACTORS*

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Abstract

This is a review paper covering the key environmental and safety issues and how they have been handled in the various magnetic and inertial confinement concepts and reference designs. The issues treated include: tritium accident analyses, tritium process control, occupational safety, HTO formation rate from the gas-phase, disposal of tritium contaminated wastes, and environmental impact--each covering the Joint European Tokamak (J.E.T. experiment), Tokamak Fusion Test Reactor (TFTR), Russian T-20, The Next Step (TNS) designs by Westinghouse/ORNL and General Atomic/ANL, the ANL and ORNL EPR's, the G.A. Doublet Demonstration Reactor, the Italian Fintor-D and the ORNL Demo Studies. There are also the following full scale plant reference designs: UWMAK-III, LASL's Theta Pinch Reactor Design (RTPR), Mirror Fusion Reactor (MFR), Tandem Mirror Reactor (TMR), and the Mirror Hybrid Reactor (MHR). There are four laser device breakeven experiments, SHIVA-NOVA, LLL reference designs, ORNL Laser Fusion power plant, the German "Saturn," and LLL's Laser Fusion EPR I and II.

There were a number of other conceptual or reference design studies available; however, they were not included in this study for the lack of any detailed treatment of the tritium handling problems.

A matrix was set up comparing each of the pertinent projects or design studies against what we have judged to be the key environmental and safety issues. In general, most of the major issues were treated by one study or another, although no study covered a substantial number of them.

The key environmental and safety issues found by our study to be neglected were: 1) accident analyses of tritium handling operations, 2) the special process control requirements for tritium and tritium-containing schemes involving forms detection, interferences, redundancy, and accountability, 3) worker safety, leak sources and surface contamination during maintenance and lack of egress routes and protective clothing, 4) disposal of tritium-contaminated waste streams and surplused equipment, and 5) enumeration of the environmental impacts involving transportation and storage, tritium release emergency actions, global monitoring, fate of tritium in various metabolic chains, and total population commitment.

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INTRODUCTION

The environmental and safety considerations for the future fusion energy electric power stations take on a special role not found in any other energy production facility today. Fusion energy can be cost-competitive even when the delivered electric power costs (¢/kW) are considerably above fossil fuel-generated electric costs, since fusion energy's environmental and social costs are so low. After all, it is the sum of the delivered costs plus the environmental and social costs that will properly establish fusion energy's role in the weave of our society.[1] It surely will be acceptable to site and operate fusion energy power stations where fission plants would never be allowed.

It is for this reason that the chemical engineering aspects of tritium management in fusion reactors must be treated especially carefully. We must not leave any potentially troublesome issue (in the public's eye) unexamined, lest it pop up as a surprise far down the time line when these reactors are being sited and started up within or near our cities. We cannot allow the tritium of the future to become the plutonium of the past.

In preparation for this paper, we prepared a compiliation of what we thought were the key environmental and safety issues and judged each of the studies world wide[2-35] for the scope of their treatment of the topics as indicated in Table I. A checkmark in the table indicates some treatment of the topic, more than a mere mention of the words. We were indeed lenient on the authors.

The next step (November 16, 1977) was to send out our extended list of key issues included in Table I and ask for suggestions of additional topics or criticism of the topics provided. The responses were good and, in a number of cases, topics were added, deleted, or altered.

The topics in Table I will now be treated in that order. Rather than simply identifying these inadquacies in the various studies and leaving the problems dangling at this point, we have attempted to assemble the best solutions and suggestions from the various study groups around the world into a set of recommended actions.

A parenthetical note should be made about the JT-60[36] Japanese large Tokamak experiment. It is indeed conspicuous by its absence from Table I. As of this writing, JT-60 will not utilize tritium in its operation and, therefore, is not further treated in this study

Now a final note of caution is in order: the paper attempts to offer selected tritium technology solutions to the key environmental and safety problems and makes no claim to exhaustively compare the tritium technology solutions available. This later task was the subject of a DOE funded "Tradeoff Study."[37]

2A

Table 1.

KEY ENVIRONMENTAL AND SAFETY ISSUES

0. Operational Date for D.T. Ignition — Year 19: -82

1. Tritium Accident Analysis

   a. Fault tree and risk analysis in process design
   b. Materials of construction and quality assurance
   c. Tritium hardware component failure mode and rate (i.e., Fittings, valves, pressure vessels, elastomers, catalytic oxidation, getters, adsorbers, cryo-removal systems, neutral beam injectors, etc.)
   d. (ALARA) cost/benefit analyses

2. Tritium Process Control

   a. Low level tritium forms detection (real time)
   b. Interferences by other beta-emitting radioisotopes
   c. Dynamic, feed-forward control for key process unit operations
   d. Fault tolerant, redundant control schemes peculiar to tritium
   e. Adaptive control and accountability systems capable of real time inventory (MBA) control and its reduction
   f. Safe-guarding of tritium as a strategic material (classification policy)

3. Occupational Safety

   a. Permeation and Leak sources
   b. Surface contamination
   c. Massive releases and spills followed by cleanup and decontamination (air or vacuum containing enclosures)
   d. Emergency Worker Egress
   e. Tritium protective suits
   f. Medical and health physics (exposures, quality factors, sensitive individuals, etc.)

4. HTO Formation Rate from the Gas Phase

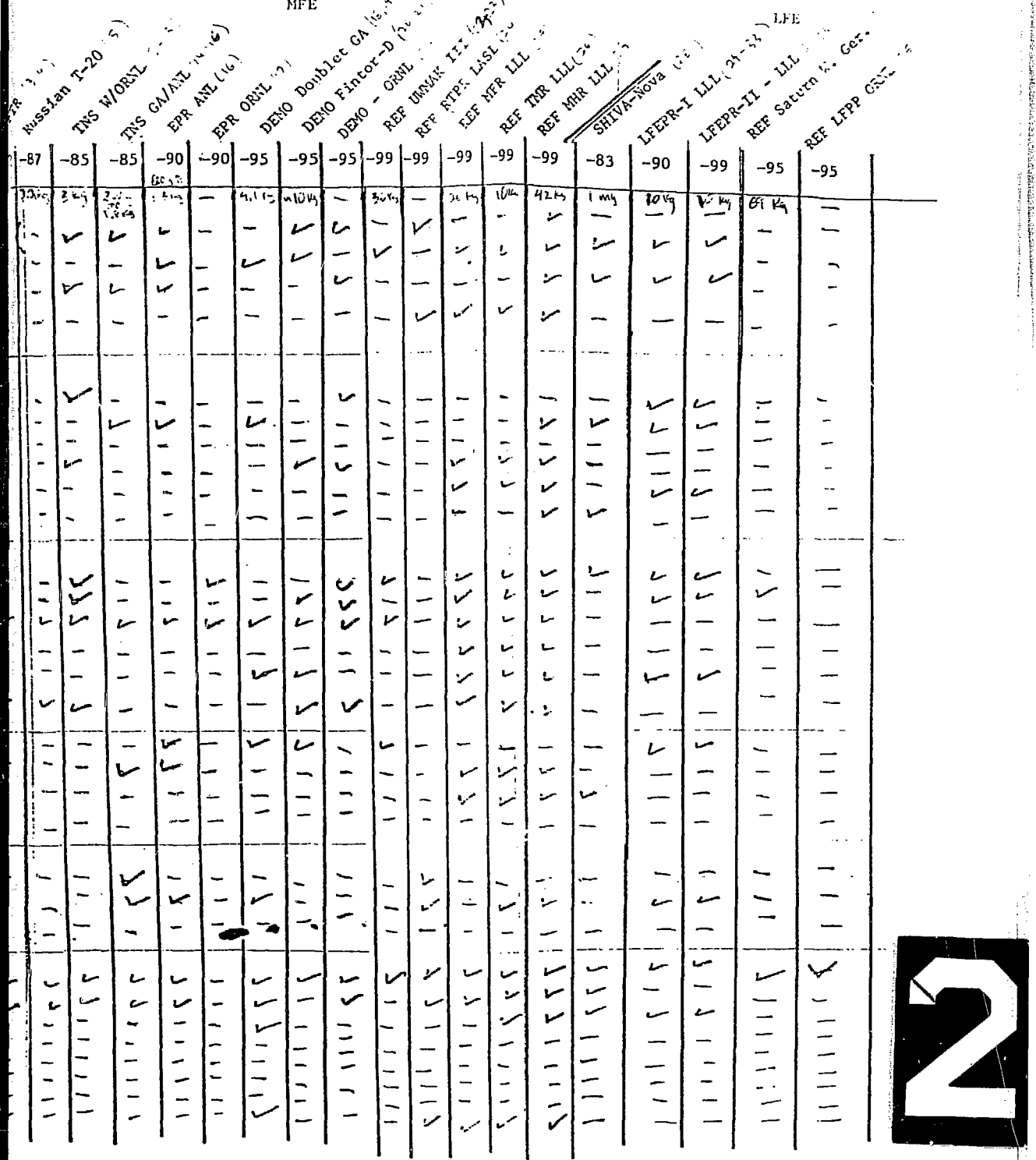
   a. In reactor blanket and coolant streams (oxid. layer control)
   b. Practical reactor hall environments
   c. Avoidance of special catalytic or high conversion reactor hall surfaces
   d. Accelerated conversion in the environment

5. Disposal of Tritium Contaminated Wastes

   a. Recovery
   b. Containerization, immobilization, and burial and/or storage
   c. Deep well injection

6. Environmental Impact

   a. Release goals and legislation
   b. Plume dispersion, building down-wash, HTO conversion, and rainout
   c. Transportation and storage
   d. Accident Release Advisory Capability (ARAC)
   e. Global monitoring (short and long term trends)
   f. Concentration in special metabolisms
   g. Fate of tritiated organics in the food chain
   h. Total population commitment


MFE
LFE
Russian T-20
TNS W/ORNL
TNS GA/ANL
EPR ANL (16)
EPR ORNL
DEMO Doublet GA
DEMO Fintor-D
DEMO - ORNL
REF UWMAK III
REF RTPR LASL
REF MFR LLL
REF THR LLL
REF MHR LLL
SHIVA-Nova
LFEPR-I LLL
LFEPR-II - LLL
REF Saturn G. Gen.
REF LFPP
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1. Tritium Accident Analyses

The fusion energy power plant designer begins with some tentative concepts as a design basis; and these have to be studied, developed into more detailed hardware specifications, and finally tested for potential hazards or accidents both to the worker and to the public and environment. The tritium process design is subjected to safety/risk analyses.[38] From these examinations, the designer learns which and how few chain events will lead to some kind of failure or accident, impacting worker, public, or environmental safety. The designer, armed with this new information, goes back to modify the process design to achieve fewer and less likely chain events to a failure. These modifications can include special tritium-compatible (certified) materials of construction and quality assurance procedures to guarantee compliance with these special materials procurement and handling methods, operating procedures, operator training, testing, inspection, preventative maintenance, etc. These modifications may involve specialized tritium-compatible (certified) hardware components such as fittings, valves, pressure vessels, dry compressors and pumps, elastomers, catalytic reaction oxidizers or getters, adsorption beds, cryo-removal systems, neutral beam injectors, in-line tritium monitors, etc., which have known (and hopefully low) failure modes and rates.

Now, if the designer proceeded in this way, he would continue along the path of correcting weaker and weaker links in his more reliable process design, but soon at greater and greater capital equipment costs. Quickly the costs would far exceed the benefits to the public and the environment. It is at this point where the ALARA (As Low As Reasonably Achievable) criteria can be applied. Based on the value of human life and risk of death when exposed to global levels of tritium water, the cost/benefit goal of $20 per tritium curie released per year can be used.[39]

To illustrate, suppose we are processing tritium contaminated stack gases being released from the fusion power plant. These gases contain tritium which has leaked from a myriad of locations in the plant, is released as part of maintenance operations, exudes from within materials as the result of permeation loss or of "soaking" effects from previous tritium concentration spikes, and finally the accident contribution (annual probability times release quantity). Suppose this annual averaged release quantity is 1500 Ci/day. One could justify a capital expenditure of ($20 x 1500 x 365) around 11 million dollars to avoid these releases. Since the tritium finds its way into the stack gases by a wide variety of routes, the designers could spend the 11 million dollars in a variety of ways (i.e., reduced failure rate, tritium cleanup systems, etc.) to get to the lowest possible release rate. Higher expenditures would not be cost effective.

There are also cost/benefit tradeoffs between the cost paid for short tritium removal processing time to cleanup an accident, and the cost of shutdown[40] after which time (re-entry time), the maintenance workers can re-enter the reactor hall for repairs. In a catalytic oxidizer/molecular sieve adsorption system, the re-entry time is roughly halved when the catalyst volume is doubled and Pt/Pd catalyst costs around $70,000 per cubic meter of catalyst. Heating the catalyst hotter also increases performance but costs more in power consumed (i.e., 1 megawatt electric for every 10°C at 60 m^3/sec flow).

So it is in this manner that the engineer should do safety/risk analyses as an integral part of the evolution of the process design and not after the fact.

Special programs at the various DOE tritium facilities addressing the special tritium problems in materials of construction and quality assurance have just been underway for a year or so. The aggrevating effects of tritium on the classical problems of hydrogen embrittlement are being faced in a number of different steel alloys. Some hard and costly lessons have been learned. One example of such specialized effects that tritium causes have been described by Gede and coworkers[41], where elevated pressure conditions of moist teflon become corrosive to 316 stainless with tritium present but not deuterium or hydrogen. Much of this experience has impact on future fusion reactor design.

There has been little coordination of these efforts in materials of construction and Q.A. for tritium systems, and it is just beginning at this time. Fintor D is perhaps the best example of the use of safety/risk analysis methods being applied to fusion reactor design.[2]

As we all move into larger tritium processing systems, the importance of developing a tritium specialized data base of experience for hardware component failure mode and rates, much has been done in the aerospace industries. A good start at this is a combination of petrochemical and refinery hydrogen technology blended with aircraft experience and tempered with tritium specialities. We have initiated interest in starting a DOE-wide testing facility for such mechanical hardware component testing in tritium service at Du Pont's Savannah River Plant and, with continued DOE support and encouragement from the tritium communities, we should be able to see such a national facility operable by 1983.

The kind of information discussed above finds its application and payoff in developing the tritium process designs via the cost/benefit analysis. As illustrated in the above example, there is the obvious tradeoff between capital expense in catalyst volume and the reduced tritium emissions to the environment. In each of the future reference designs, equipment demonstrations, and early reactor design scoping studies, we should faithfully apply the concepts of cost/benefit to judge the "proper" level hardware and thus expense that is justified for tritium safety. If we do not, but retrogress into the arbitrary goal or standard, we leave ourselves open to criticism as to absolute motherhood judgments without recourse to any technical facts.

2. Tritium Process Control

Nearly every design group made reference to the need for specialized tritium process control, raising a number of specialized points here and there about the difficulties generally involving the interferences of other beta-sources or needs for redundant equipment.

The problem begins with the instrumental difficulty of detecting low level tritium forms (discriminating gas from water) on the real-time basis required for

process control. Historically, a variety of concepts have been tried, utilizing ionization chambers before and after water traps to produce the differential gas/water readings. Electronic noise, non-linearities in response, contamination of the ionization chamber volume, and poor resolution have led these attempts to failure. With the introduction of improved, stable, solid state electrometers of special sensitivity and digital output that can be instantly processed by minicomputer, we are nearing the point of demonstrating the feasibility of such low level forms discrimination. Early LLL tests have shown that qualitative discrimination is observed with low level gas and water. Further tests must be done with carefully calibrated gas/water standards now to quantitatively demonstrate the success of this approach.

Interferences by other beta-emitting radioisotopes have been studied by Roland Jalbert at LASL over the last several years.[42] A prototype instrument design is being evolved that will probably serve the needs.

The next area of challenge is one of demonstrating dynamic, feed-forward control of the key process unit operations such as catalytic oxidation, adsorption, condensation, cryotrapping, distillation, and storage systems. Each of these unit operations are inherently unsteady state operations. For example, the catalyst must be activated and heated before a large tritium gas spike hits the bed, the adsorption bed capacity depends on previous breakthrough front position, condensation depends on volumetric capacity and history, cryotrap performance rate depends on the film thickness already laid down, distillation units must handle surging flows, etc. Feed-forward models are needed to set the operating conditions of these units before the unsteady tritium levels are applied and the units must be operated to minimize inventory and document contents.

Dynamic performance models are just now being developed for some of these units. The next step is to utilize these dynamic models to establish the process control transfer functions needed to specify the instrumentation response requirements and specifications. This kind of work will continue on TFTR, TSTA, and JET. Published literature from petrochemical industries and academic chemical engineering research groups is helpful, but must be tempered by the specialities of this tritium-customized equipment--small inventories, remote operations, redundant key operating functions, redundant controls, and fail-safe shutdown systems.

The points about fault-tolerant, redundant control schemes peculiar to tritium needs to be expanded. By fault-tolerant, we refer to control systems that are designed using modern methods of distributed computer control systems where there are several levels of controllers. The first level may be a microprocessor located at the particular unit operation, hardware component items (catalytic oxidizer, adsorber bed, still, etc.) which has "hardwired" instructions on the fail-safe shutdown modes (i.e., dump tritium into uranium trap, isolate a system, etc.) and how to automatically and remotely function to achieve a fail safe state. It can also have stored the allowed operating states and the safe control instruction sets the unit is allowed to receive from the next hierarchical controller and also the disallowed operations. So each unit has its own self-stored allowed operating instructions. If the unit is asked to perform operations which it "knows" would be unsafe or would result in a number of other disallowed consequences, it will transmit an alarm condition. Such information on allowed

and disallowed states ought to be derived from a fault-tree analysis of the entire system, where the minimum cut sets involving that unit are stored in that μP (microprocessor). In this way, if a number of related units are in certain operating states, the decision of whether this unit can operate in proper concert can be made based on knowledge of its critical surrounding units.

Redundant flow paths and/or operating trains must also be provided so that component or flow path failures can be bypassed by the control system in order to best continue to function safely. This field of computer control has evolved in other industries in the U.S. to a high enough level of sophistication that it can be applied directly to this problem.

The next area of challenge is that of achieving the design of adaptive control and accountability systems capable of real time inventory (MBA) control and its reduction. This is particularly specialized to tritium. Our tritium facilities who perform these tasks manually now have benefitted from the experience of operating unit history where reliable and acceptably accurate estimates can be made of the tritium holdup in a particular operating unit. Much of this experience can be provided in the form of unit performance models that contain the dynamics and operating performance predictive capability to give the tritium holdup information needed for the DOE accountability purposes. Even in our process designs, we consider the best units which are amenable to convenient or more accurate analyses to give these tritium holdups. For example, hydride beds that have been under variable and rather unknown operating conditions are very difficult units for which to establish tritium accountability estimates. This is also time for distillation columns, cryotraps, adsorption beds, etc.

Now to make the above problem even more challenging, there is the well-motivated desire to continually and dynamically attempt to minimize tritium inventory. This is where the concepts of adaptive control may enter. The overall material balances of the entire plant, with the addition of the unit performance models described above, produce an inventory quantity of tritium. This quantity can then be used in heuristic algorithms to try out changes in the control functions and control strategy of the plant operation in order to minimize the objective function of tritium inventory. Although this is a relatively new field, there is much that can be done to operationally control the plant operation to minimize inventory based on experience of other industries which maximize product quality, minimize operating costs, energy losses, environmental releases, etc.

And now finally the question of safe-guarding of tritium as a strategic material needs to be examined. DOE's Division of Safeguards and Security issued a memorandum[43] soliciting comments on the completeness and appropriateness of a list of factors providing the basis for the placement of tritium under complete safeguards following an overall tritium study effort. It would not be appropriate to discuss the details here, however, it should be sufficient to list the five potential reasons given for applying safeguards to tritium. They are: (a) stragetic materials, (b) health hazards, (c) social/psycological, (d) economic value, and (e) abundance/commerce in material--sources and end usage. The survey was taken. We all provided comment. The study effort was started at Brookhaven National Laboratory, and then placed on hold until the Center Energy Plan could be more fully developed; so we have a reprieve.

These deliberations impact the U.S. and probably world-wide efforts in fusion energy development by adding to our present fusion reactor development and design considerations additional controls on tritium which will be complete and exhaustive. In discussion of the issues with the appropriate DOE staff, we have identified a number of critical factors: protection from malevalent acts of all process streams containing significant amounts of tritium, enclosing of all facilities containing tritium within a guarded DOE exclusion area, classification of key tritium purification and concentration unit operations, and inspection and surveillance of personnel entering and leaving the area for security clearance and any possible possession of tritium.

Application of such constraints would severely hinder the present international flavor and open cooperative scientific nature of the U.S. and world-wide research programs. But it is up to each of us to provide the proper technical basis and assurances to delay such heavy constraints on tritium. We should be thinking about the possible approaches in our designs of means to prevent malevalent acts on process units or piping trains containing significant quantities of tritium. We should also be thinking carefully about tritium classification policy and the critical tritium technologies we should consider worth protecting. It might be possible to provide bases where these critical tritium technologies could be avoided in fusion reactors and where the problem may simply reduce to guarded or secured vaults within the plant as opposed to classifying the whole operation. It is up to the technical tritium community to provide the acceptable arguments, means and methods; for if we do not, others will do it for us in undesirable ways.

3. Occupational Safety

More than all the other environmental and safety issues, occupation safety of the plant worker handling tritium, tritium-containing or contaminated equipment was most thoroughly covered by the various studies. Mostly permeation of tritium through the equipment was treated; however, it is the combined permeation and leak sources and contact with surface-contaminated equipment that is most important. Leaks, of course, result in normal every day operations as the price of doing business. There is continual maintenance of equipment and cleaning operations which involve disassembly of equipment where small volumes containing tritium are opened to the reactor hall atmosphere and tritium-contaminated surfaces are newly exposed to the atmosphere and are allowed to outgass slightly. Our experience indicates that these activities contribute a greater dose to the worker than any other exposure route. Although accidental spills have and will continue to provide extreme routes for worker dose; however, air flow system designs have historically been configured to keep the worker well isolated from the accident. In this way, even the accident mode, integrated over the worker's history at the job does not contribute significantly, compared to the sum of routine doses for physical contact.

Nearly every study addressed the problem of massive releases and spills followed by cleanup and decontamination. Only two of the studies (14, 15, 27, 39, 40), however, addressed the key issue of the role of leak sources and surface outgassing upon the sizing of the cleanup system and the impact on the cleanup time. This is a particularly difficult technical challenge when operating cost considerations for high flow rate cleanup systems force one into a "room temperature" (i.e., 40-80°C) catalytic oxidizer. As of this writing it appears to be "solved" (40) through the use of special catalyst, high temperature, oxidizing activation procedures, and paper catalyst reactor design. Low levels may require tritiated methane removal steps.

Now the above discussion applies to air-containing reactor hall atmospheres. It is the presence of the nitrogen and somewhat the oxygen and the ambient humidity or water content which makes this problem as difficult as it is. However, the use of evacuated reactor halls or outer containment structures offers a number of advantages (20), the most significant of which is the reduction of other diluents (i.e., air, inert gases, ordinary water, etc.) that must be co-processed with the tritium spill. The absence of these diluents permit massive reduction in the costs of such cleanup systems owing to reduced heating and cooling loads, volumetric flow capacity, quantity of catalyst, catalyst deactivation constituents, etc. All of these features are indeed positive, however. There is one very significant problem -- tritium contamination of the huge vacuum pumps required to evacuate the reactor hall or outer containment structure. If these vacuum pumps contain oil, there is a severe oil handling and disposal problem. If the vacuum pumps are oilless compressors, the large surface areas of turbine blades, etc. will be tritium contaminated. Of course, the vacuum pump exhaust would be tritium processed before exhausting to the environment. If these problems can be solved, evacuation offers significant advantages to tritium safety in addition to the other significant physics and mechanical advantages.

The remaining three occupational safety issues have nearly all been neglected and they are: worker emergency egress, tritium protective suits, and special problems in establishing safe tritium working levels. In all DOE tritium facilities we have provided emergency crash door exits from laboratories to get the worker out quickly to avoid significant contaminated air exposures in case of accidents. This concept is satisfactory in laboratory-scale operations, but when the scale becomes as large as a power plant (i.e., two football fields in area) the escape time downstairs, scaffolding, etc., becomes significant. Tritium mixes and diffuses in air much faster than a worker can escape to avoid the cloud dilution (i.e., molecules move at the speed of sound in air). Accidents producing cloud concentrations of around 1,000 ci/m^3 diluted to μCi/m^3 levels provide large concentration during forces for cloud disposal by diffusion. We have proposed (25, 27) breathing booths where "telephone booths" supplied with fresh air are placed strategically throughout the plant to allow worker escape. These booths can be fitted with an escape route through the large air ducts feeding the booths. For reactor halls with inert gas and evacuated conditions the worker escape situation becomes even more challenging.

Tritium protective suits have evolved in Canadian HWR operations to nearly acceptable levels of protection factors[44] to offer worker protection in cases of fusion reactor tritium accidents.[25,27] The present limitation on further increases in protection factors above 1500 appear to be the junctions between the various suit flaps. In experimenting with these "state-of-the-art" suits, we found that air flows needed to be substantial in order to avoid gross degradation in worker operational efficiency. Air hose connections to work stations plus an emergency air supply and automatic valve appear to help solve these efficiency declining factors. Questions about whether the worker routinely wears this suit in normal operation so that he is prepared for the accident or not is a risk-versus-cost question. Such concepts can be very effectively tested at TSTA.

Medical and health physics has set the safe tritium working level limits for a rather small, highly monitored and select population of tritium workers in the world. When fusion reactor operations become significant, the worker population being exposed to tritium will substantially increase, and this situation raises questions as to other cumulative radiation exposures, domestic and occupational, possible low level, non-threshold effect, sensitive individuals etc. The biological quality factor for the radiation from tritium has been taken as unity, but sensitive conditioning can occur where increases by a factor of five or so should be considered.[45] These concerns involve tritium water. We have suggested[25,27] reactor hall operation levels below 40 $\mu Ci/m^3$ composed of 5 $\mu Ci/m^3$ water and the rest gas, with worker scheduling to aim at 20% MPC levels. This now appears to be feasible.

The water (HTO or T_2O) form of tritium is some 400 times more toxic to humans than is the gas form. Consequently, the formation rate of the water species is very important. This point was only occasionally raised in the studies. We reviewed the literature earlier[25] and found the conversion rate from the gas to be slow, but still significant at levels that might exist following an accident.

This water conversion rate has been used by several studies to be an advantage in reactor blanket and coolant streams by the formation of a form of tritium which is impermeable through the walls.[13,17,21,22] It is argued that the addition of excess oxygen into the coolant (i.e., helium) will convert all of the tritium gas contaminant to HTO which will not permeate out and can be trapped by in-line adsorbents. This would be very fortunate if the conversion occurred sufficiently fast without a catalyst and the HTO was indeed impermeable. I will not debate these points, but simply state there is a myriad of conflicting evidence and the phenomenon and success of this approach will have to be demonstrated.

The oxidation of Incolay 800 steels used in commercial reactor steam generation has been demonstrated [46-48] to create an effective oxide barrier to tritium permeation. This is indeed a useful concept for fusion reactors. It is true that thermal transients can fracture this brittle film, but it does repair

itself and can eventually continue as an effective barrier (46). We must be cautious that extrapolating these results out of the concentration or driving force range for which the experiments are applicable, and we must allow for permeation losses during thermal upsets. Otherwise, Incoly 800 steam generators look encouraging. It is possible other alloys or other coolant compositions could make further gains. A word of warning is in order here, however. Reducing permeation losses to vanishingly low levels ignores the fact that tritium leakage will occur in normal operations and will probably dominate permeation leak rates. Also, NRC design guidelines may well force the designer into allowing for tritium leakage into the coolant from the breeding pins at 1% of the inventory in order to be licensable.

There is another concern about HTO conversion rates in practical reactor hall environments. The presence of hot metal surfaces, catalytic surfaces, elastomers, paints adsorbed room moisture, radiation fluences from the machine, all slightly enhance the conversion rate. Here again it is hoped that TSTA will establish what conversion rates can be expected in practical atmospheres. Although many of the studies have suggested that conversion will be so low as to be a nonproblem, these arguments are based on theoretical homogeneous kinetic rates of clean systems and the practical atmospheres will be far different. When we establish the particular surfaces which are special catalytic or high conversion reactor hall surfaces, we can then avoid these surfaces in our reactor hall designs.

HTO conversion rates are also of concern in the environment as well. Releases of tritium gas are considered to be substantially less serious (i.e., 400 times) than releases of HTO; however, this neglects accelerated conversion mechanisms in the environment which have been observed and documented in France (49) and at Savannah River (50). Apparently, the key ingredients are certain green plants and bacterially active soils. Vegetative matter somehow assimilates a large amount of tritium from the surrounding air and distributes the tritium as HTO within its vegetative water. These considerations are important to the understanding of the fate of tritium in the environment. For example, rainfall somehow exchanges water with that within the vegetative material and produces HTO contaminated surface water which percolates into the ground and/or produces runoff to streams or storm sewers. The HTO seems to eventually appear in sewage plant effluent and in the drinking water supplies (51). Whatever the detailed mechanism seems to be, the end result appears to be a more rapid communication between the gaseous tritium release plume and the ground water. Thus, it appears that environmental models that yield total global population dose can be based upon drinking water consumption.

5. Disposal of Tritium Contaminated Wastes

There are a number of tritium waste streams in the fusion power plant that deserve special consideration for treatment and recovery of tritium. All of the air containing an inert gas containment atmospheres that are processed by means of catalytic oxidation and molecular sieve adsorption can be utilized for tritium recovery by means of the regenerator of the sieve and electrolytic breakdown of the HTO into its component gases. If the tritium-contaminated atmosphere contains ordinary water diluting the HTO to less than 100 ppm or so, it rapidly becomes uneconomical to recover tritium. It is for this reason that we strive to restrict the water content within these

streams to as low levels as practicable. The other reason for restricting water levels in the gas/water conversion rate problem discussed earlier in this paper.

When ambient humidity is present in the reactor hall air, some 50 bbls of tritium-contaminated water must be disposed of -- as a low level waste (52). This is a significant problem, which can be reduced somewhat in its environmental impact by means of humidity reduction to 5% relative humidity or so (25, 27). The evacuated reactor hall or outer containment approach (20) will eliminate this problem altogether. Restricting humidity to low levels, around 5% relative humidity, would allow the occupational worker restricted entry without protective suits. However, lower levels, evacuated reactor halls, or inerting, of course, would require suited occupational workers.

There are also tritium contaminated oil waste streams (predominately from vacuum pumps) which will require disposal. Such quantities could be about 5 bbl/day. At this time we do not appear to have the technology for economic recovery of the tritium contents of these waste oils. Consequently, we should adopt the philosophy of preprocessing and scavening these streams for tritium before they enter the vacuum pumps.

significant tritium waste stream that continues to be neglected is that of solid wastes with tritium surface contamination. These waste streams are particularly troublesome because they are bulky and continually outgas tritium water (HTO) into their container (i.e., usually 55 gal drums). The handling problem is made particularly difficult because the equipment items cannot be disassembled without significant protection of the worker. Besides, much of the equipment being discarded does not economically warrant disassembly. We have proposed a partial solution to this problem by providing a large, hermetically-sealed waste storage room, the atmosphere in which is tritium processed by catalytic oxidation and water adsorption. The room would contain a large overhead crane for handling the wastes and provide access into a large vacuum oven. It might also be possible to design another vacuum oven with an internal compactor or crusher to substantially reduce the volume of the material, break open some of the closed or trapped volumes containing tritium, and form the waste into cubic and standard sized and shaped blocks for further encapsulation and disposal. The gaseous effluent from the vacuum oven would, of course, be processed as discussed above.

These wastes, involving drums of water or oil and compacted solids, could be combined and cast (encapsulated) into large concrete blocks further immobilizing the solids. Such encapsulation can provide additional assurance that groundwater or air would not effectively circulate through these wastes, further eluding tritium into the environment. If the concrete block is made large enough, the half-life of tritium (12.3 years) will decay away the majority of the tritium before it can permeate through the concrete to the outside.

The co-presence of other activated radiation products seriously complicates these problems of tritium handling. This is another reason why we have proposed such a waste handling facility as outlined above. These operations with other radioactivation products present can be viewed simply as a sorting and search operation -- trying to disassemble and locate and remove those parts which are particularly activated. It is for this reason that we have taken special pains in our fusion reactor designs to avoid such highly activated products. If we can ensure that the activation is indeed low level, then these activation products could be left in the tritium-contaminated wastes, encapsulated and disposed of together. Otherwise, they must be removed by remote manual operations which are costly and time-consuming.

Besides burial and/or storage, the use of deep-well injection should be seriously considered. The idea is to deposit liquid wastes into a geologically inactive area which is free of groundwater movement. Holding these tritiated wastes for 100 years would remove 99.97% of the tritium by decay to helium, 300 years would remove all but about 3 ppb. It appears that geological records should be adequate to provide isolation from 100 to 300 years.

6. Environmental Impact

In the design of fusion power plants the tritium release goals will probably never be set by legislation, but instead be left in the DOE parlance as ALAP (as low as practicable) (53), since they will be design and process dependent. ALAP for light water reactor (LWR) routine operation is taken to mean 5 mrem at the fenceline, based on that industry's demonstration that this low level was currently achievable by available technology (54). This would represent the most

Clearly, however, without specialized legislation directly applicable to fusion, the most applicable today, is the new NRC (54) regulations of 170 mrem annually applied to all "nuclear fuel cycle operations." This would permit 350 Ci/day as routine tritium releases averaged over the year. This same legislation sets one-time accident doses to the general public as 5 rem, or releases of around 1 Kg of HTO from a plant or a 1 square mile site with a 30 m stack located at the property center and annual average U. S. meteorological conditions. Most of the foreign studies (2, 20, 21, 34, 49) have come to approximately the same conclusions.

Since one of the major attractions of fusion is its minimal environment (compared to fission), it is relevant to ask how much further can we go in reducing emissions and providing better environmental impact analyses. As discussed earlier in this paper, an excellent test in the cost/benefit sense is ALARA. Invoking this test as \$1,000/man-years within a 50 mile radius (55), a 1 Kg release of HTO from a fusion power plant located at LLL with clear weather, worst-case meteorology (i.e., 95% conf. limit) would result in about 2.5×10^6 man-rem of exposure mostly in the San Francisco Bay Area. ALARA suggests that \$$2.5 \times 10^6$ could be spent in order to avoid this accident. Similarly, \$$5.6 \times 10^3$ could be spent to avoid a 200 Ci accident,, etc. This latter level of expenditure would be typified by the addition of a redundant catalytic oxidizer bed of 0.1 m^3. So further reductions would be justified according to these above criteria.

There is also the possibility (56) that fusion would be expected to meet or exceed some of the licensing criteria NRC uses for LWR's, such as requiring full operation with 1% of the breeding blanket pins failed or 5,000 Ci, whichever is greater, and releasing extra tritium into the coolant while not exceeding 5 mrem at the fence. For routine operation it is suggested that design bases be set for 0.05 mrem at the fence, if it can be shown to be cost effective according to the ALARA criteria.

Our examination (27) of the impact of these fusion criteria being applied to a fusion reactor where tritium is bred in sealed fuel pins has indicated that 1% failure of 85,000 pins could release 4220 Ci/day into the coolant and eventually 29 Ci/day to the environment. The ALARA test interpreted for routine releases using a total population commitment model (39) as $20 per Ci/year, would justify a 200×10^3 expenditure to avoid these releases. If we argue expenditures like this could reduce the tritium pin failure rate to 0.1%, an ALARA balance would be roughly achieved. Such releases of 3 Ci/day by this route would yield fenceline doses some 40 times less than the NRC's 170 mrem and would just meet the 5 mrem criteria. The design could not meet the 0.05 mrem criteria and still be cost effective in the ALARA sense.

These illustrations, I hope, give you some idea of how low the release goals for tritium can be below available legislation and still be cost effective in the ALARA sense. With this as the background, we will now illustrate what improvements should be possible in the environmental impact analysis for tritium.

The first area is that of plume dispersion, building down-wash, HTO conversion, and rainout as applied to tritium. Most of the background in this area of atmospheric dispersal applies to radioisotope releases from fission reactors. Not all of this background applies directly to tritium. Plume dispersion dynamics should be better for tritium (a hydrogen gas isotope) than heavy fission products owing to tritium's low density and very large molecular diffusion coefficient, these factors do not enter into the simple Gaussian models and are therefore, I feel, underestimating tritium dispersal characteristics in practice.

All of the accident analyses covered in the available studies have assumed that the tritium release will occur up the 30 m stack and not at roof or ground level. These accident modes are possible and clearly place the on-site people at higher risk than previously estimated. Releases at roof or ground levels will yield ground level concentrations dominated by building downwash aerodynamics. This field of aerodynamics is progressing at a fast rate today, and in a few years, these questions of environmental impact can be adequately answered and will no longer be a point of question. Our experience has indicated that tritium releases in confined areas disperse quickly owing to tritium's (HT and HTO) large molecular diffusion coefficient and low density. We believe near-ground level releases will be tolerable.

Water conversion (HT to HTO) in a release plume has been a subject of environmental impact controversy, but need not be, since it is conventional practice for DOE's tritium facilities to calculate ground level doses based on instantaneous and complete conversion before release. So this assumption is very conservative and over estimates the impact.

Rainout of tritium-contaminated water droplets from a plume is another mechanism that could potentially increase ground-level doses. Accidental releases can occur during foggy or rainy weather, whereupon the precipitation falling through a tritium gas or water vapor cloud could exchange with the tritium and become contaminated before hitting the ground. This mechanism is different than the rainout of fission products normally treated. It most likely will be less serious in that the exchange process between the precipation and the plume is much less efficient than the rainout of the dense fission product particles normally treated. We have started making measurements of rainout of tritium from our studies during rainy weather to get a rough experimental measure of the magnitude of the effect. There is also the unlikely possibility that the tritium accident would produce tritiated solids which would rainout like fission products. The transportation and storage of tritium is another area which received only occasional treatment by the study groups. TFTR is the first group[3,4] that is actually having to firm up plans and schedules. The early machines will draw on DOE supplies and probably use ground transportation methods that are presently in use. Air transport has been severely restricted owing to political pressures from environmental groups. The DOE approved tritium gas transportation vessels consist of two sizes of "Savannah River Cans" (5 g and 20 g) held at about 1.5 atmospheres at maximum. They are equipped with secondary containers and means for sampling the secondary container atmosphere to insure integrity of the primary inner vessel. These vessels have been used extensively for nearly twenty years and indeed have a good record. Some tests are needed on cyclic fatigue of the primary inner vessel valve, as it is normally used as a handle for removal of this inner vessel from the secondary container; otherwise these vessels could be adopted directly. DOE ground transportation is by specially constructed, secure and hardened trucks, which are carefully routed and kept under constant surveillance. Their exact position is known at all times. These means should offer extreme protection against accidents which would release large quantities of tritium into the population.

Similar atmospheric or sub-atmospheric level storage of the gas has been planned by many of the study teams, as indicated in Table I. Efforts have also been made to divide the storage inventories between several tank farms in order to achieve reduced vulnerability to tank damaging accidents or sabotage. Tanks are frequently buried and located remotely from the main reactor hall. There is also planned the possibility for hydride storage of the tritium which offers the economic attraction of reduced tank volume at low pressure. The disadvantages include requiring heating for regeneration of the tritium for service. Again, this is a cost/risk tradeoff.

As larger quantities of tritium are involved in fusion reactor use, each of the facilities should plan on joining the Accident Release Advisory Capability (ARAC).[5,7] These facilities have the capability of providing near real-time predictions of the propagation of a tritium spill cloud across the U.S. and much of the world. It obtains meteorological records and keeps a running account of the dispersion of the tritium plume and estimates ground level concentrations and human exposures as it proceeds. We have recently been developing the tritium instrumentation interfaces required for this capability.

Tritium in the global environment has been monitored extensively by Ostlund[58] through the period of atmospheric testing, the moratorium, the resumption of

testing, the halt, and the testing of the Chinese, French, Russian, Indians, etc. Recently, such monitoring data has been reported by Ostlund.[59] A review of the available literature has been made by Jacobs.[60] The global atmospheric inventories of tritium are still dominated by the tritium released when atmospheric testing was being done, and the tritium release source terms (Ci/day) are presently predominantly from LWR's and tritium production and handling facilities.[25,27] Source terms of tritium from fusion reactors in the range (1-10 Ci/day) will not become significant (10% of the 15,000 Ci/day being produced in the stratosphere by cosmic rays) in the global inventory until we have at least 1500 plants in operation. Fuel reprocessing plants as we have known them, releasing about 1500 Ci/day, have been shut down. It is likely that these kind of releases will not continue from this source. If fuel reprocessing does continue, the tritium releases are most likely to be in the 1-10 Ci/day range, in which case, these sources of global tritium will not be significant.

Tritium concentrations in special metabolisms are generally covered only in selected species.[44,45,49-51,60] It is clear that special metabolisms have the apparent ability to concentrate the tritium. The mechanisms are not well understood, nor are the consequences. As the analytical instrumentation sensitivities are becoming considerably improved, it is now possible for various groups (including environmental groups) to detect threshold levels far below what has formerly been possible. Since tritium is not found naturally (other than its small generation rate by cosmic ray bombardment of the stratosphere), one must ask what is the consequence. Is it significant at these low levels?

These factors lead one to the next question about the fate of tritium and its tritiated organics in the food chain.[45,50,51,60] Tritium in vegetative water is well documented[51] and provides the route via grazing cows for tritium to get into milk, domestically consumed. It is this latter route which we have selected as being the most sensitive and critical in establishing the safe levels of tritium release for normal operations and accident conditions.[51] To be exceedingly conservative, it is assumed that new-born infants consume their entire milk supply from cows that have exclusively fed on the vegetative matter containing elevated levels of tritium. As long as tritium releases are low, such conservatism will remain tolerable, otherwise considerably more research will be required on the fate of tritium in the food chain.

The last area is that of total population commitment,[39] or the number of human deaths that are expected to globally result from release of tritium into the atmosphere, assuming a linear (no-threshold) relationship between tritium radiation dose and carcinoma-caused deaths. It is this latter criteria that we have merged with the ALARA criteria in order to establish the cost/benefit guideline of $20 per Ci/year for the economic cut-off for capital expenditures for hardware justified to remove tritium from fusion reactor hall or containment atmospheres.[39] We have illustrated the use of such guidelines earlier in this paper and find it to be quite useful. We recommend this approach on all future reference design studies.

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