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OVERVIEW OF FUSION REACTOR SAFETY

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SUMMARY

Nuclear fusion represents one of a limited number of inexhaustible energy options for the future. Fusion as a source of commercial power is at an early stage of development, with power stations expected to be ready for commercial use early in the next century. On the basis of current conceptual designs, design trends, and preliminary safety assessments, it appears that the health and safety risks to the public from this technology are as low or lower than other "inexhaustible" energy technologies. In addition, the early stage of development of fusion provides the ability for continued improvement in the safety-related aspects of material selection and design.

Use of deuterium-tritium burning fusion reactors requires examination of several major safety and environmental issues:

1. Tritium inventory control

2. Neutron activation of structural materials, fluid streams and reactor hall environment

3. Release of radioactivity from energy sources including lithium spill reactions, surperconducting magnet stored energy release, and plasma disruptions

4. High magnetic and electromagnetic fields associated with fusion reactor superconducting magnets and radio frequency heating devices

5. Handling and disposal of radioactive waste.

Early recognition of potential safety problems with fusion reactors provides the opportunity for improvement in design and materials to eliminate or greatly reduce these problems. With an early start in this endeavor, fusion should be among the lower risk technologies for generation of commercial electrical power.

1. INTRODUCTION

Present trends in magnetic fusion research and development indicate the promise of commercialization of one of a limited number of inexhaustible energy options early in the next century. Operation of the large-scale fusion experiments, such as the Joint European Torus (JET) and Tokamak Fusion Test Reactor (TFTR) now under construction, are expected to achieve the scientific break even point. Early design concepts of power producing reactors have provided problem definition, whereas the latest concepts, such as STARFIRE, provide a desirable set of answers for commercialization. Safety and environmental concerns have been considered early in the development of magnetic fusion reactor concepts and recognition of problem areas, coupled with a program to solve these problems, is expected to provide the basis for safe and environmentally acceptable commercial reactors. First generation reactors addressed in this paper are expected to burn deuterium and tritium fuel because of the relatively high reaction rates at lower temperatures compared to advanced fuels such as deuterium-deuterium.

This paper presents an overview of the safety and environmental problems presently perceived, together with some of the programs and techniques planned and/or underway to solve these problems. A preliminary risk assessment of fusion technology relative to other energy technologies is made. Improvements based on material selection are discussed. Tritium and neutron activation products representing potential radiological hazards in fusion reactors are discussed, and energy sources that can lead to the release of radioactivity from fusion reactors under accident conditions are examined. The handling and disposal of radioactive waste are discussed; the status of biological effects of magnetic fields are referenced; and release mechanisms for tritium and activation products, including analytical methods, are presented.

2. TECHNOLOGY COMPARISONS AND RISK ASSESSMENT

Fusion reactor development has several positive aspects when comparing safety and environmental issues with other energy producing systems. Some of the key positive aspects are

(1) Clean operation with no undesirable emissions such as SO_2, NO_2, and CO_2 that cause serious degradation of air quality.

(2) Self-contained fuel processing with insignificant fuel transportation problems.

(3) Little potential for an overpower condition, since an increase in plasma power generally causes an increase in plasma impurity from the first wall, with consequent reduction or termination of the plasma burn.

(4) Relatively low power density operation compared with fission reactors, thus reducing the severity of coolant disturbances and afterheat removal problems.

(5) Quantity of radioactive material in a fusion reactor controlled to some extent by design. The tritium inventory and neutron-activated structures are the major contributors to fusion reactor radioactivity.

(6) Potential for development of advanced fuel cycles and improved materials, reducing the radioactive inventories involved in the use of fusion for commercial power.

Kazimi [1], of the Massachusetts Institute of Technology, has recently performed a comparative assessment of the risk to society from fusion power compared with that from other technologies for generation of commercial power, e.g., fission, coal, solar. This analysis compared the total risk involved in mining, manufacturing, construction, transportation, operation, and decommissioning of the various types of power plants. The analysis of fusion plants contained several significant assumptions due to the current stage of development of the technology. Preliminary results shown in Figure 1 indicate that the risk to society from fusion is as low or lower than that from other technologies. Such analysis will be refined as data permit and used to improve the overall safety of fusion power plants.

The use of probabalistic risk assessment to evaluate failure paths early in the development stage of fusion reactors permits safety concerns to be included during the design stage. The technique is effectively applied to systems that have detailed design information available. The Tritium System Test Assembly (TSTA) under construction at the Los Alamos Scientific Laboratory represents a system with adequate design detail for tritium fueling [2]. Using TSTA design information, probabalistic risk assessment is presently being applied to fusion reactor tritium system design. Magnet systems, first wall-blanket coolant systems, and vacuum systems will also be included as detailed design information is developed. The end result will be fusion reactor system designs that meet regulatory requirements in a quantitative manner.

3. SAFETY AND ENVIRONMENTAL FACTORS IN MATERIAL SELECTION

Fusion reactors are not limited to use of specific materials for the construction of structures that must contain the plasma and blanket breeding system. Material selection must be based on performance requirements (including both normal and transient conditions of temperature, pressure, combined stresses, fatigue, and swelling characteristics under intense neutron irradiation) and compatibility with the various proposed coolant and breeding materials. The proposed choices range from highly developed, austenitic stainless steel to ceramic structures such as silicon carbide. The safety and environmental factor of greatest concern in material selection is the inventory of activated structural material. Figure 2 shows the activity of several proposed fusion reactor structural materials as a function of decay time following reactor shutdown. Large differences (nine orders of magnitude) between the metals and ceramics occur following a short decay period. The advantage of the relatively low activity of ceramic structures provides a challenge to ceramic engineers to develop the methods and techniques needed to obtain the reliability of metallic structures.

4. RADIOLOGICAL HAZARDS

Fusion reactors, as presently conceived, will contain two major sources of radioactivity; tritium and neutron-activated structures and materials. The tritium inventory, followed by the activation products produced in the reactor are discussed. In addition, fusion reactors operating on fuel systems other than deuterium-tritium (D-T) are under study, and these systems would eliminate tritium as a fuel, with obvious safety advantages. The difficulties, however, in obtaining the required temperatures and confinement times required for these advanced systems preclude use of advanced fuels in first generation reactors and are therefore not considered in this paper.

4.1 Tritium

Tritium emits a low energy (6 keV average) beta particle and is therefore biologically active only when inhaled, ingested, or absorbed in the body. Tritium in the oxide form (T_2O or HTO) has a maximum permissible concentration (MPC) for the general public 200 times lower than the elemental (T_2 or HT) form. Oxidation rates of tritium in the environment have been estimated at about 1%/day based on accidental release [3]. Additional research is required to quantify oxidation and exchange reactions under conditions expected in fusion reactor containments.

The tritium inventory in a fusion reactor is a complicated function of reactor power level, plasma physics, fueling system design, and blanket breeding technology. The reactor power level determines the mass rate of tritium entering into fusion reactions to produce the required energy [about 400 to 450 g/day for a 1000 MW(e) plant]. This usually represents a small fraction of the system inventory. Plasma physics considerations, primarily helium ash and impurity control, influence the fractional fusion fuel burnup. The fractional burnup determines the tritium recycle required in the reactor fueling system. For example, the fractional burnup for the latest reactor concept, STARFIRE, is approximately 0.40 compared with earlier Tokamak concepts ranging from about 0.01 to 0.05. The holdup in various fueling system components such as the cryopumps and cryodistillation units represents a significant fraction of the tritium inventory. Lithium as a liquid metal, mixtures of lithium-lead, or lithium compounds such as lithium oxide or lithium aluminate have been proposed for breeding tritium. The inventory of tritium in the blanket depends on the required extraction process concentration and blanket system design. Inventory values vary from 1 to 50 kg of tritium for the STARFIRE concept and early UWMAK concepts, respectively. The extraction processes represent an area of uncertainty that can influence tritium inventory in the blanket by approximately an order of magnitude.

In addition to the above areas, tritium storage represents a specialized area of large tritium inventory. The amount of storage will depend on the expected outage time for the various tritium fueling systems. The storage area can be isolated from the reactor and is small enough to provide multiple containment to appropriately reduce the tritium release probability from the storage facility.

4.2 Neutron Activation

Approximately 80% of the energy generated by the D-T fusion reaction is in the form of 14.1 MeV neutrons. In addition to the structural damage caused by these high energy neutrons, activation of structural materials, reactor hall atmosphere, and coolant streams lead to safety concerns.

Structural activation of fusion reactor first wall-blanket concepts has been well documented [4,5]. Depending on construction material selection, activity levels vary from gigacuries for stainless steels to an amount more than nine orders of magnitude lower for graphite and silicon carbide after a short period of decay. Decay heat removal for most of the metallic structural materials of practical interest represents a safety concern primarily because of the potential for mobilization and transport of these radioactive species under severe accident conditions. The decay heat level in fusion reactors is about an order of magnitude less severe than fission reactor core decay heat. Nevertheless, the level is not trivial, as indicated by calculations of first wall structure temperatures after reactor shutdown for a loss-of-coolant-flow accident. The temperatures for several structures, coolants, and breeding materials are shown in Table I. The results show equilibrium temperatures above the material yield strength for some of the cases, requiring either auxiliary cooling or redesign.

Structural activation represents both a maintenance and waste management safety and environmental concern, in that remote handling technology and shielding requirements will play a major role in reducing personnel exposure to as low as reasonably achievable levels. Low activation ceramics such as SiC have the potential to significantly alleviate these concerns.

Coolant systems have the potential to transport activated material to areas outside the reactor shield. The coolant and/or impurities in the coolant can be activated by neutrons in the blanket. Corrosion and erosion of activated first wall-blanket structures into the coolant and neutron sputtering of activated structures into the coolant are also sources for radioactive material transport. Plateout of this material in heat exchangers and piping represents an additional shielding problem and must also be considered in pipe break accident analysis. An example of neutron sputtering from a stainless steel first wall into a helium coolant system, resulting in possible contact dose levels of 100 rem/h in the coolant manifolds, is described in Reference [6].

Air activation of reactor hall atmosphere by neutrons penetrating the reactor shield is a potential problem. Some of the short-lived and long half-life nuclides of concern include ^{13}N, ^{16}N, ^{41}Ar and ^{3}H, and ^{14}C and ^{39}Ar, respectively. The reactor shield requirements for superconducting magnet and personnel protection should also include evaluation of the atmosphere activation in the reactor hall to determine the limiting factor.

5. ENERGY SOURCES

Energy sources represent a potential means to cause release, volatilization, and transport of radioactive species beyond the confines of designed barriers and shields in the reactor. Therefore, radiological safety concerns for the general public and operating personnel require detailed examination of these sources. These sources, discussed below, include the plasma, the blanket energy including lithium fires, and superconducting magnets.

5.1 Plasma

The primary energy source in a fusion reactor is the plasma, which is relatively dilute when compared with fission reactor cores, i.e., 4 to 10 MW/m^3 and 40 to 500 MW/m^3 power densities, respectively. The total energy in the plasma of a fusion reactor producing 1 GW of electrical power is about 1 GJ. It can, therefore, be seen that the safety concerns regarding the primary energy source of fusion reactors represents a different level of concern when compared with fission reactors. The concern is primarily operational in nature. Plasma disruptions in which the plasma is quenched by interaction with limiter and first wall structures represent the major concern. The potential consequences of disruptions with safety implications include first wall failure and volatilization, and failure of the vacuum system, including cryopumps, as a secondary effect. Experiments that would illustrate the consequences to first wall structures from plasma disruptions are needed to provide the data necessary to design prevention and/or mitigation systems. Some designs for the International Tokamak Reactor (INTOR) and the Fusion Engineering Device (FED) use carbon tiles on the first wall for protection.

5.2 Blanket Energy

The blanket area of fusion reactors thermalizes and absorbs the fusion neutrons, transfers the heat from these reactions to a primary coolant, and breeds tritium from the lithium material contained in the blanket. Liquid lithium represents one of several chemical forms under consideration for tritium breeding. The advantages of liquid lithium as opposed to other chemical forms of lithium include excellent heat transfer properties, good tritium breeding capabilities, and simplicity in design. The major disadvantage stems from potential reactions of lithium metal with other materials under spill conditions. Lithium spill experiments have provided data to evaluate the consequences of these reactions [7]. Figure 3 shows the effect of a lithium spill into an air containment. Lithium pool temperatures approaching 1200°C are reached, which is well below the theoretical flame temperature of 2500°C for the reaction with air. Lithium also reacts with concrete, liberating heat and hydrogen. The LITFIRE computer code has been developed by the Massachusetts Institute of Technology (MIT) to model lithium spill accidents in containment structures [8,9]. Mitigation of the consequences of lithium spill accidents includes using a vacuum or low oxygen containment atmosphere, stainless steel liners over concrete, and compartmentalization.

Alternate lithium compounds and mixtures such as lithium oxide, lithium silicate, lithium aluminate, and lithium-lead are under consideration for tritium breeding blanket material. The advantage of these materials is the negligible or reduced chemical reactivity compared to liquid lithium. For example, the lithium-lead materials react with air with reduced activity compared to lithium metal. The disadvantage of the compounds is reduced tritium breeding capability, requiring a neutron multiplying material such as beryllium or lead. Tritium extraction techniques represent a problem for all of the above materials, which can result in much higher tritium inventories in the blanket compared with the use of lithium metal.

5.3 Superconducting Magnet Energy

Superconducting magnets that will be required for power producing fusion reactors contain significant stored energy. The toroidal field coils of STARFIRE contain 50 GJ of stored energy. The safety concerns are related to the release of this potential energy in an uncontrolled manner. The structural integrity of these systems is under analytical and experimental examination in programs such as the Large Coil Program (LCP) at Oak Ridge National Laboratory for both normal and off-normal loads. Further studies are required to accurately assess the course of a large magnet quench and to develop the design approaches that detect and provide for safe disposal of this stored energy when required. In addition, eddy currents during magnet and plasma transients couple the magnet energy to the plasma and other fusion reactor structures. Analytical and experimental studies are in progress at Argonne National Laboratory, MIT, and other laboratories to provide data to quantify these effects.

6. HANDLING AND DISPOSAL OF RADIOACTIVE WASTE

The quantities of tritium flowing through the reactor fueling system, and bred and extracted from the blanket-lithium system require special equipment and material handling methods and procedures. The TSTA will provide tested techniques, methods, and procedures for the safe handling of fusion reactor fueling systems. Some examples of these techniques include maintenance procedures using specially designed glove boxes to service tritium fueling components, and methods of packaging tritium contaminated materials, such as lubricating oil, for ultimate disposal.

Structural materials under consideration for conceptual fusion reactors such as STARFIRE require periodic replacement during the facility lifetime due to neutron damage. For example, STARFIRE estimates the replacement material for the blanket to be 140 tonnes/year. A large amount of activated material, such as stainless steel, will therefore be generated during the facility lifetime. Removal and replacement of this material will require the application of remote technology and clever design to ensure an economical and reliable system. Large fusion experiments (such as TFTR and JET) that expect to use tritium will require remote handling equipment to reduce maintenance doses. Long burn devices such as FED and INTOR will be required to come to grips with the problems of handling large quantities of highly activated materials in complicated geometries as a normal operation.

Transport and storage of fusion reactor radioactive waste represents a technology presently under development for fission reactor systems, with the added advantage of greatly reduced biological hazards since fission products and actinides are absent from fusion wastes. Preliminary studies [10] indicate that interim storage followed by reprocessing of at least some of the waste may be feasible for fusion reactors.

7. MAGNETIC AND RADIOFREQUENCY (RF) FIELDS

Occupational exposure to magnetic fields in fusion reactors is a potential safety concern. The large fields generated by superconducting magnets may lead to excessive personnel exposure. A good review of the effects in humans and animals is provided by Schiff in Reference [11]. Interim standards for only occupational exposure have been suggested for existing and planned magnetic fusion test facilities in the U.S. by a committee chaired by Dr. E. L. Alpen under the auspices of the Assistant Secretary for the Environment (Department of Energy). For example, for an 8-h workday, whole body exposures should be limited to 0.01 tesla for constant dc fields. The committee has also recommended support of additional research to study chronic mammalian effects, teratogenic and mutagenic effects of acute and chronic exposure, effects on reproduction and fertility, and effects on central nervous system and sensory motor functions.

Radiofrequency heating has assumed increased importance in magnetic fusion devices. The development of more detailed designs will determine if personnel exposure is a concern. Studies along the lines of magnetic field exposure may be required.

The control of magnetic and RF fields in fusion reactors to prevent public and personnel overexposure does not appear to be a difficult problem. Proper design offers a reasonably straightforward solution.

8. TRITIUM RELEASE

The release of tritium to the reactor hall and to the environment represents the major safety concern for fusion reactors. Release of tritium can occur from accidents, permeation through structure containers, and during maintenance.

Accidental release of tritium to the reactor containment and environment can occur by failure of tritium containing systems. The methods to prevent and/or mitigate the release of tritium under these conditions are under study at several laboratories around the world. The TSTA will provide some of these data. Techniques presently being studied include multiple containment, compartmentilization, and emergency cleanup systems. Multiple containment systems include glove box techniques for tritium systems that are at low temperature and pressure and have little potential for explosion and/or missile production. Monitoring of the glove box atmosphere provides detection against primary containment failure. For tritium containing systems at elevated temperatures and pressures, double piping with annulus detection may be required. Compartmentalization of tritium systems outside the reactor structure can reduce the consequences of severe accidents. Isolation techniques between compartments are a part of the design. Accidents that spill tritium into the reactor hall will require extensive emergency cleanup systems. Typical systems under study pump a fraction of the reactor hall atmosphere into a catalytic converter where all elemental hydrogen isotopes, including tritium, are converted to the oxide. The contaminated atmosphere containing the tritiated water is then pumped to condensation units where most of the water is condensed. Condensation units are backed up by molecular sieve adsorption units to remove final traces of tritiated water.

Consequence analysis of tritium spill accidents that include biological uptake effects have been performed [12]. Mechanistic accident scenarios of spill accidents that include the results of improved safety design and reaction rate research are needed. Containment design for tritium accidents will require further study.

Tritium permeation through structural and heat exchange material represents an operational and environmental concern in fusion reactors. This is especially true in the blanket breeding and heat exchange zones because the tritium is present at relatively high temperatures, which favors high permeation rates. Tritium permeation studies have shown large variations [13,14]. Buildup of protective barriers such as oxide films are believed to cause at least some of the data variation. Further studies are required to take advantage of protective films in the design of fusion power reactors to reduce tritium permeation.

Maintenance of tritium containing systems may be the most difficult area to control [15]. The operation of TSTA and other dedicated tritium facilities are expected to provide the designs and operating procedures to ensure acceptable tritium exposures during maintenance conditions. Operational data from large fusion experiments using tritium will provide useful information for designing maintenance systems for commercial reactors.

9. ACTIVATION PRODUCT RELEASE

The mobilization, release, and transport of activation products requires the coupling of large energy sources with activated structures. Coupling can occur in the blanket region following a coolant disruption accident without adequate shutdown systems and/or emergency coolant, depending on design arrangements. Liquid lithium spills can potentially provide the energy required to heat gases and generate chemically active aerosols that can mobilize and transport activation products. Plasma disruptions and large magnet transients have also been proposed as potential energy coupling sources. Experiments to study the mobilization and transport of activation products will provide data for use in fusion reactor transient models to realistically analyze accidents of this type.

10. CONCLUSION

The development of fusion technology to generate commercial power is not entirely free of risk or safety problems. The significant safety and environmental concerns involve the use of tritium in the fuel cycle, generation of activation products by high energy neutrons, and the fact that energy sources, if uncontrolled, could result in the release of a fraction of these radioactive inventories. However, early recognition of potential problems provides the opportunity to eliminate or greatly reduce these problems. On the basis of the early start in addressing the safety issues, fusion should provide a low risk technology to generate commercial electric power.

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TABLE I. EQUILIBRIUM AFTERHEAT TEMPERATURES FOR SEVERAL FUSION REACTOR BLANKET SYSTEM CONCEPTS

Blanket-Coolant-Breeder System	First Wall Equilibrium Afterheating Temperature Following Reactor Shutdown (K)
Stainless steel-helium-liquid lithium	1056
Stainless steel-water-liquid lithium	890
Titanium-helium-liquid lithium	926
Stainless steel-helium-solid lithium aluminate	1390
Stainless steel-water-solid lithium aluminate	1120

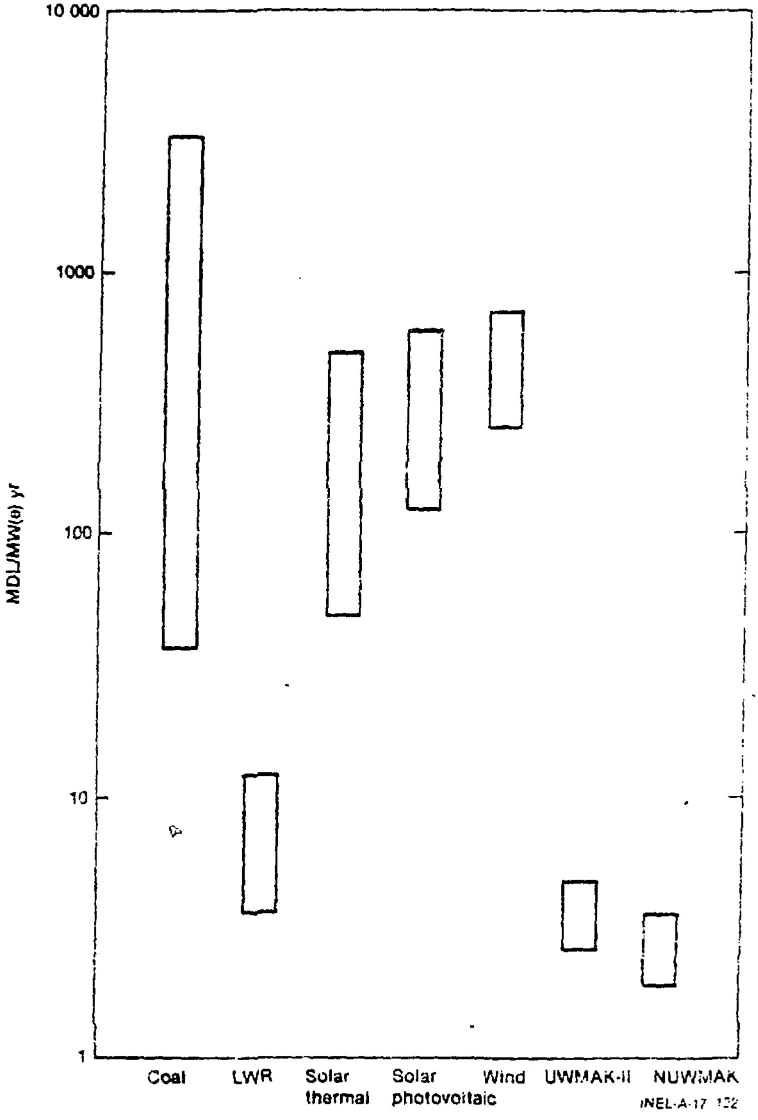

Figure 1. Risk assessment of several energy systems expressed as mandays lost (MDL) per megawatt electrical year.

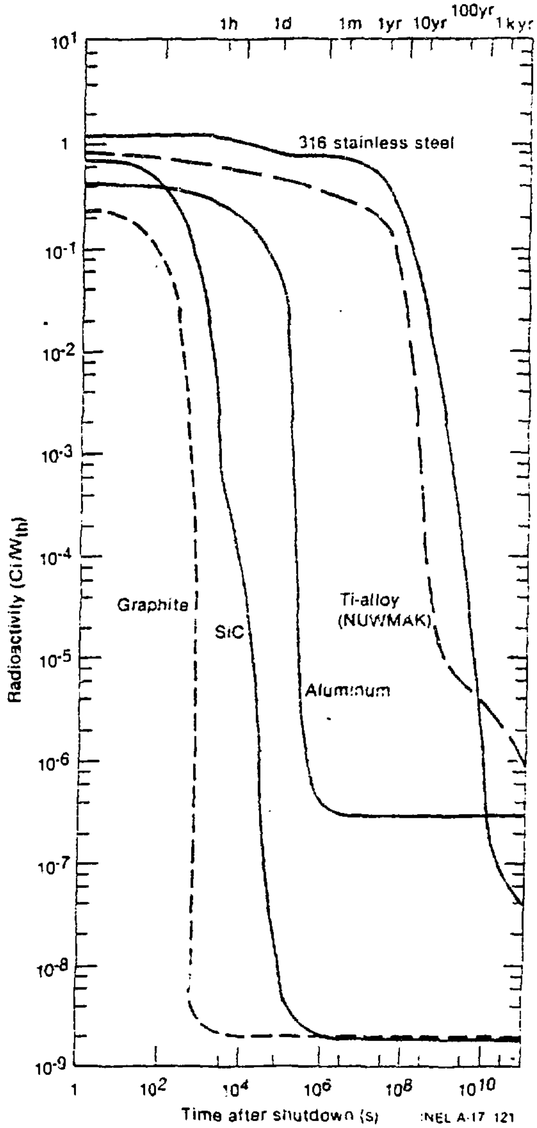

Figure 2. Postshutdown radioactivities for several fusion reactor first wall-blanket structures after two years of operation at 1.5 MW/m^2 neutron wall loading.

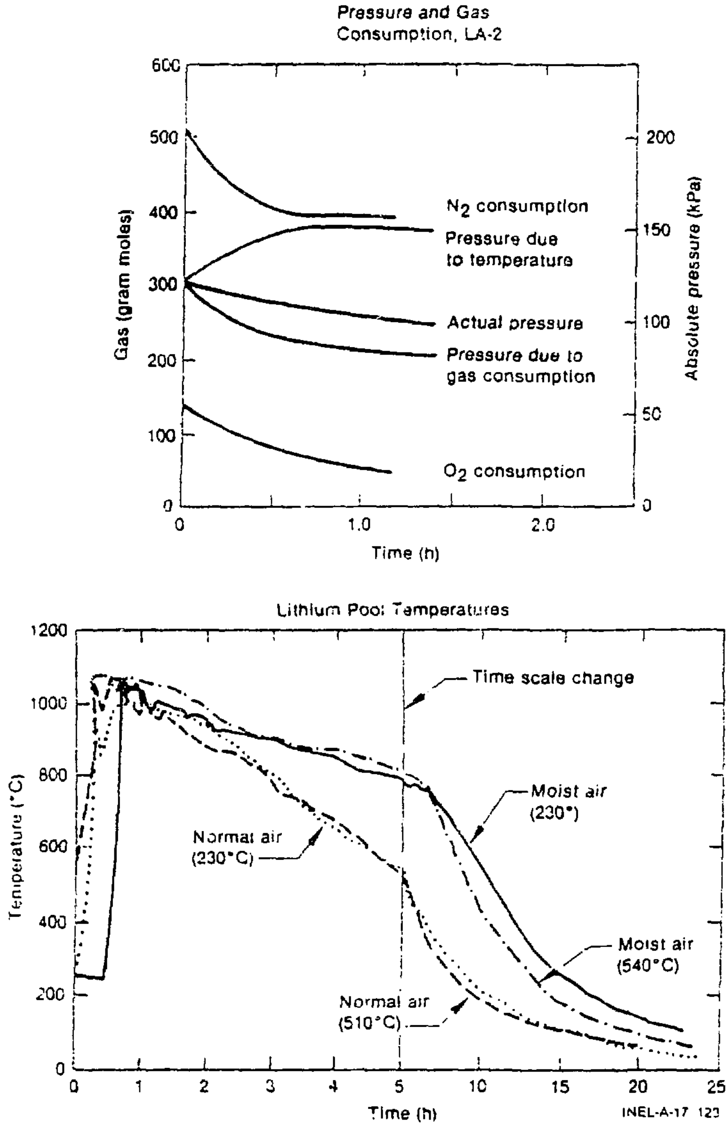

Figure 3. Lithium pool reaction in air. (Conditions: 10 kg lithium at 230, 510, and 540°C; 0.2-m^2 pool in 14-m^3 vessel.)