KfK 3834
Januar 1985

Safety Aspects of an Inertial Confinement Fusion Reactor

G. Keßler, E. G. Schlechtendahl
Institut für Neutronenphysik und Reaktortechnik
Institut für Reaktorentwicklung

Kernforschungszentrum Karlsruhe

KERNFORSCHUNGSZENTRUM KARLSRUHE
Institut für Neutronenphysik und Reaktortechnik
Institut für Reaktorentwicklung

KfK 3834

Safety Aspects of an Inertial Confinement Fusion Reactor

G. Keßler
E. G. Schlechtendahl

Kernforschungszentrum Karlsruhe GmbH, Karlsruhe

Kernforschungszentrum Karlsruhe GmbH
ISSN 0303-4003

SAFETY ASPECTS OF AN INERTIAL CONFINEMENT FUSION REACTOR

Summary

Releases into the environment of radioactive materials contained in heavy ion fusion (HIF) reactor plants must be prevented by similar safety design concepts as they are applied to present fission converter (e.g. LWR's) and breeder reactors (LMFBR's). This study is intended to identify significant safety aspects of inertial confinement fusion power plant concepts and to relate them to the more familiar basis of knowledge about the safety and the hazards of other advanced nuclear power reactor systems such as the LMFBR. Needs for safety related research and development specifically for inertial confinement fusion will be pointed out.

SICHERHEITSASPEKTE VON TRAEGHEITSFUSIONSREAKTOREN

Zusammenfassung

Die Freisetzung radioaktiver Stoffe aus Trägheitsfusionsreaktoren muß durch ähnliche Sicherheitskonzepte unterbunden werden wie bei heutigen Spaltungsreaktoren (Leichtwasser-Reaktoren und Brutreaktoren). Diese Studie soll wesentliche Sicherheitsaspekte von Reaktoranlagen auf Trägheitsfusionsbasis identifizieren und sie zu der vertrauteren Wissensbasis in Beziehung setzen, die hinsichtlich Sicherheit und Gefährdungspotential anderer fortschrittlicher Leistungsreaktorsysteme (wie Schneller Brutreaktoren) bereits besteht. Erfordernisse für speziell auf Trägheitsfusion ausgerichtete Forschungs- und Entwicklungsarbeiten werden aufgezeigt.

CONTENTS

SAFETY ASPECTS OF AN INERTIAL CONFINEMENT FUSION REACTOR

INTRODUCTION AND STATEMENT OF PROBLEM

Releases into the environment of radioactive materials contained in heavy ion fusion (HIF) reactor plants must be prevented by similar safety design concepts as they are applied to present fission converter (e.g. LWR's) and breeder reactors (LMFBR's). The safety concept of these present commercial fission reactors can be described by the "defense in depth concept" with protection systems for accident prevention and multiple containment barriers between the radioactive materials and the environment. Present safety regulations and siting criteria for nuclear power plants will certainly also have to be applied to future commercial size fusion power reactors.

Radioactive materials contained in a HIF reactor plant are:

- tritium in the fuel cycle of the plant,
- activated debris material from burning pellets within the reactor cavity,
- activated structural and shielding material of the reactor,
- activated coolant in the coolant circuits,
- activated structural material in the beam channels and the shielding of the focussing magnets.

GOALS OF THE INVESTIGATION

This study is intended to identify significant safety aspects of inertial confinement fusion power plant concepts and to relate them to the more familiar basis of knowledge about the safety and the hazards of other advanced nuclear power reactor systems such as the LMFBR.

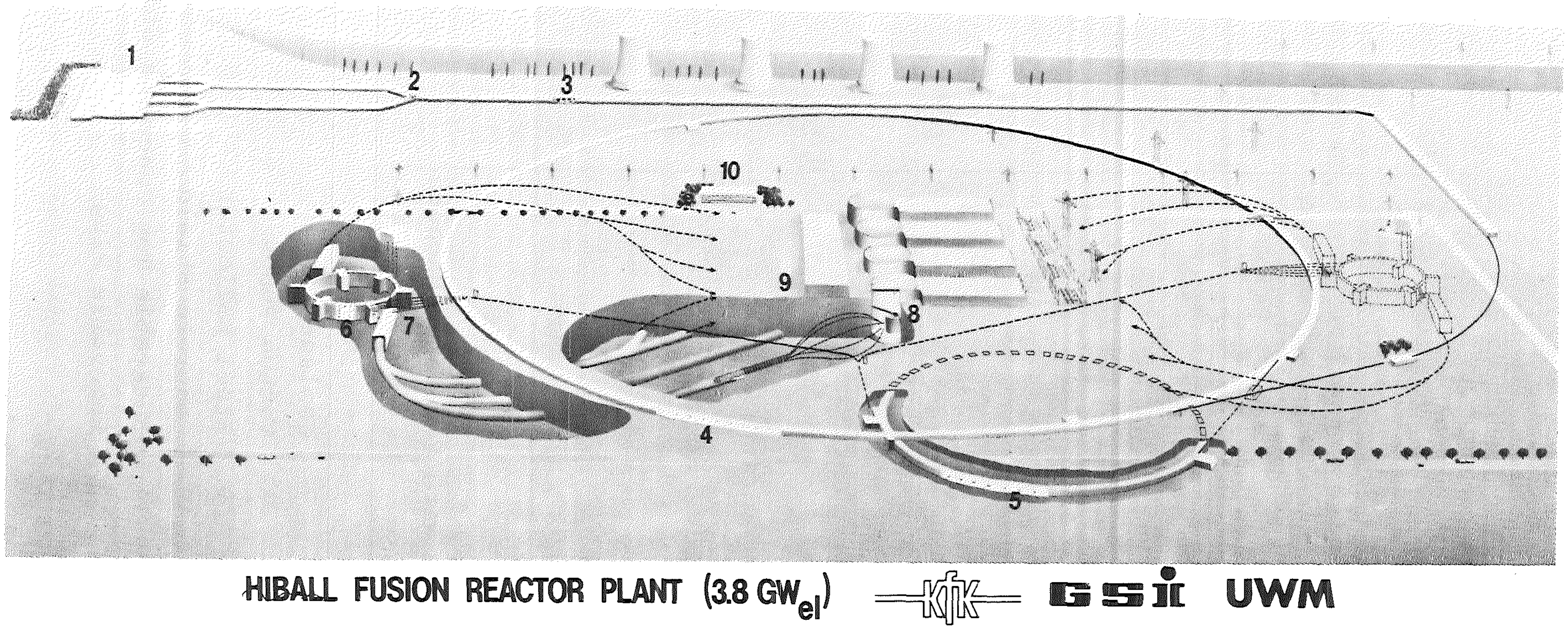
The HIBALL design study will be used as a reference for an inertial confinement system [1, 2]. The results of INTOR, Phase One [3], are used for the comparison with magnetic confinement fusion.

In many respects, a safety and hazards analysis of inertial confinement fusion can only be very preliminary, as the necessary level of design detailing is by far not yet achieved. Hence, the study will concentrate more on inherent features and on the potential sources of hazards (radioactive and toxic materials, potential sources of destructive energy releases) than on sequences of events (failures and protective measures) which might lead to release of hazardous material to the environment. A primary goal of this study is to indicate critical areas where safety related research and development will be required specifically for inertial confinement fusion, while in other areas inertial confinement fusion can benefit from the existing and still developing base of knowledge of LMFBRs and magnetic confinement fusion reactors.

HIBALL PLANT DESCRIPTION

The Heavy Ion Beam Inertial Confinement Fusion Reactor Study "HIBALL" assumes four reactor chambers with a gross thermal power of 10.2 GW and a net electric power of 3.8 GW (see Figure 1). The reactor chambers are each driven at 5 Hz by pellet explosions initiated by 10 GeV $^{209}Bi^{+}$ ion beams. The beams themselves are generated by a linear accelerator of 3 km length and a number of compressor and storage rings.

The high electrical power is typical for heavy ion beam Inertial Confinement Fusion (ICF) reactors, since the pulse energy of about 5 MJ required to ignite a pellet by inertial confinement can only be generated by big accelerator systems which have inherently high repetition rates of 20-30 Hz. As the reactor chambers are operated at 5Hz, four to six such chambers can be driven by a single accelerator system. Twenty beam channels guide 2.5 kA ion beams of 20 ns duration into the reactor chamber. All 20 beams are focussed by strong magnets at the reactor chamber entrance onto a spot size of about 7 mm diameter. The fuel pellets are injected at 5 Hz frequency with a velocity of 200 m/s from the top of the reactor chamber. They are hit by the beams when they reach the center of the chamber. The pellets are spherical and consist of several layers of different materials. The



1	Ion Sources and RFQ Linacs	6	2x5 Storage Rings
2	Funneling Section	7	4x5 Induction Linac Compressors
3	Alvarez Linac	8	Reactor Chamber
4	Transfer Ring	9	Target Factory
5	5 Condenser Rings	10	Control Building

Figure 1. HIBALL reactor arrangement: Schematic of the reactor plant layout

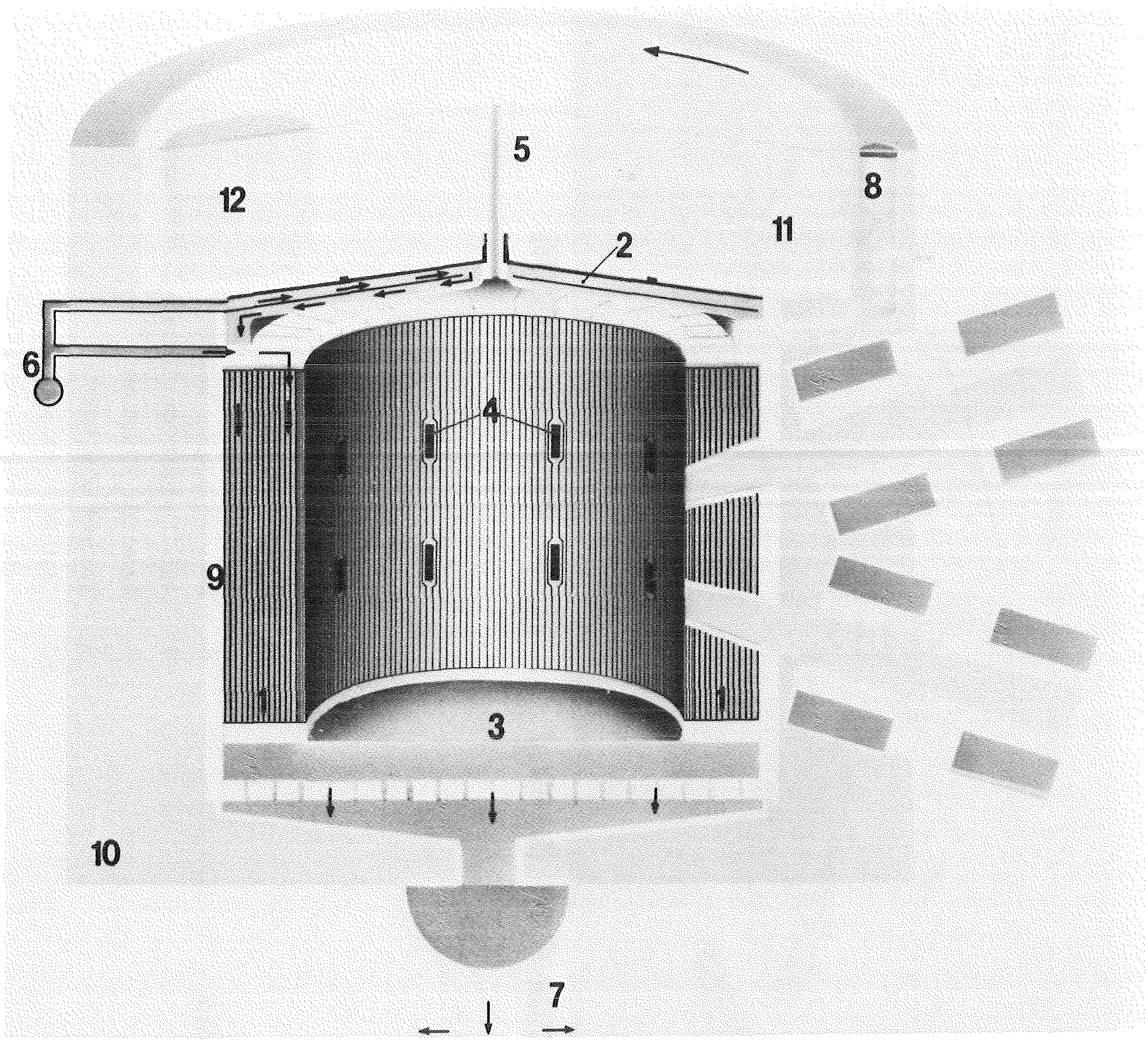


Fig. 2: HIBALL Reactor Chamber with Focussing Magnets

1	Lateral INPORT Blanket	7	Coolant Exit
2	Top INPORT Blanket	8	Vacuum Pumps
3	Bottom Pool	9	Steel Reflector
4	Beam Ports	10	Concrete Shield
5	Pellet Injector	11	Rotatable Top Concrete Shield
6	Coolant Intake	12	Removable Plug

Figure 2. HIBALL reactor chamber: Cross-section of the layout

innermost layer is cryogenic (4 K) D-T-fuel, followed by a pusher ablator and a tamper shell of $Pb_{83}Li_{17}$ and lead. The outer diameter of a pellet is 7.3 mm and roughly matches the focus size of the overlapping ion beams. The pellets for HIBALL will have to be mass produced at a rate of at least 20 per second. Some details on pellet manufacturing can be found in [4].

Figure 2 shows a schematic view of a reactor chamber which has a diameter of 14 m and a height of 12 m. The chamber tank is surrounded by a 40 cm thick lead-lithium cooled steel reflector and 350 cm of water cooled concrete. On the inner surface, the steel tank is protected by the coolant breeder ($Pb_{83}Li_{17}$) streaming through hollow plate structures and pipes braided of SiC fiber. These so-called INPORT tubes [5] allow the bulk of the coolant to flow from the top to the bottom of the reactor cavity in a controlled way (Figure 3). At the same time, some of the coolant will penetrate and wet the outer surface of the tubes. The thickness of the liquid film on the outer tube surface is sufficient to absorb the X-rays and the debris from the exploding target, thus effectively protecting the structural components. The 10 m long INPORT tubes are arranged in two tube banks. The inner bank contains 3 cm diameter tubes in a tight arrangement to remove the high heat flux caused by X-rays and ion debris (175 W/cm^2). The second tube bank is made up of 10 cm diameter tubes and will remove most of the kinetic energy of the neutrons and provide the tritium breeding. The thick region of both tube banks reduces the displacement damage caused by the neutrons in the steel wall of the reactor chamber.

The reactor chamber is held at 10^{-4} Torr vacuum in order to lower the interaction of the Bi^+ ions with the atmosphere of the reactor chamber and to allow the tritium diffusion out of the coolant. Vacuum pumps are provided to reduce the chamber pressure between target explosions below 10^{-4} Torr.

The innermost INPORT tubes will withstand the radiation load for about two years. For their replacement the vessel cover can be rotated. It contains a removable plug through which both the ceiling structure and the wall elements can be removed and replaced individually.

The final focussing magnets have to withstand the radiation damage and nuclear heating caused by fast neutrons. The magnet design in HIBALL uses either normal or superconducting magnets. Normal conducting coils can be used close to the beam pipe and to the reactor, whereas the power saving superconducting coils are arranged in better protected locations.

The coolant is heated from 330 to 500°C in the reactor chamber. Four primary pumps take the hot coolant from the lower pool within the

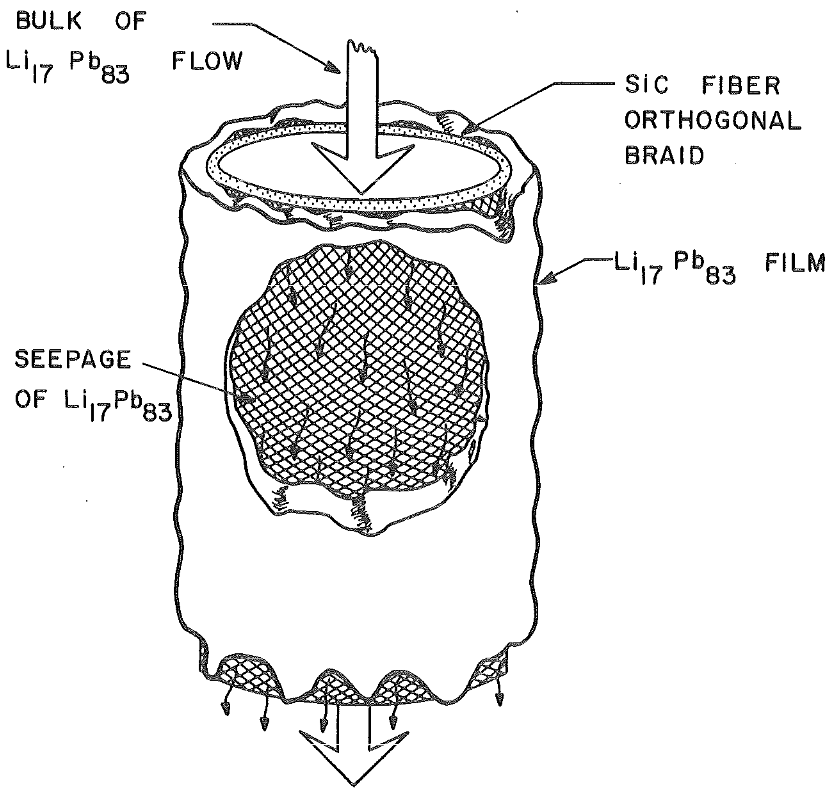


Figure 3. Concept of INPORT Tubes

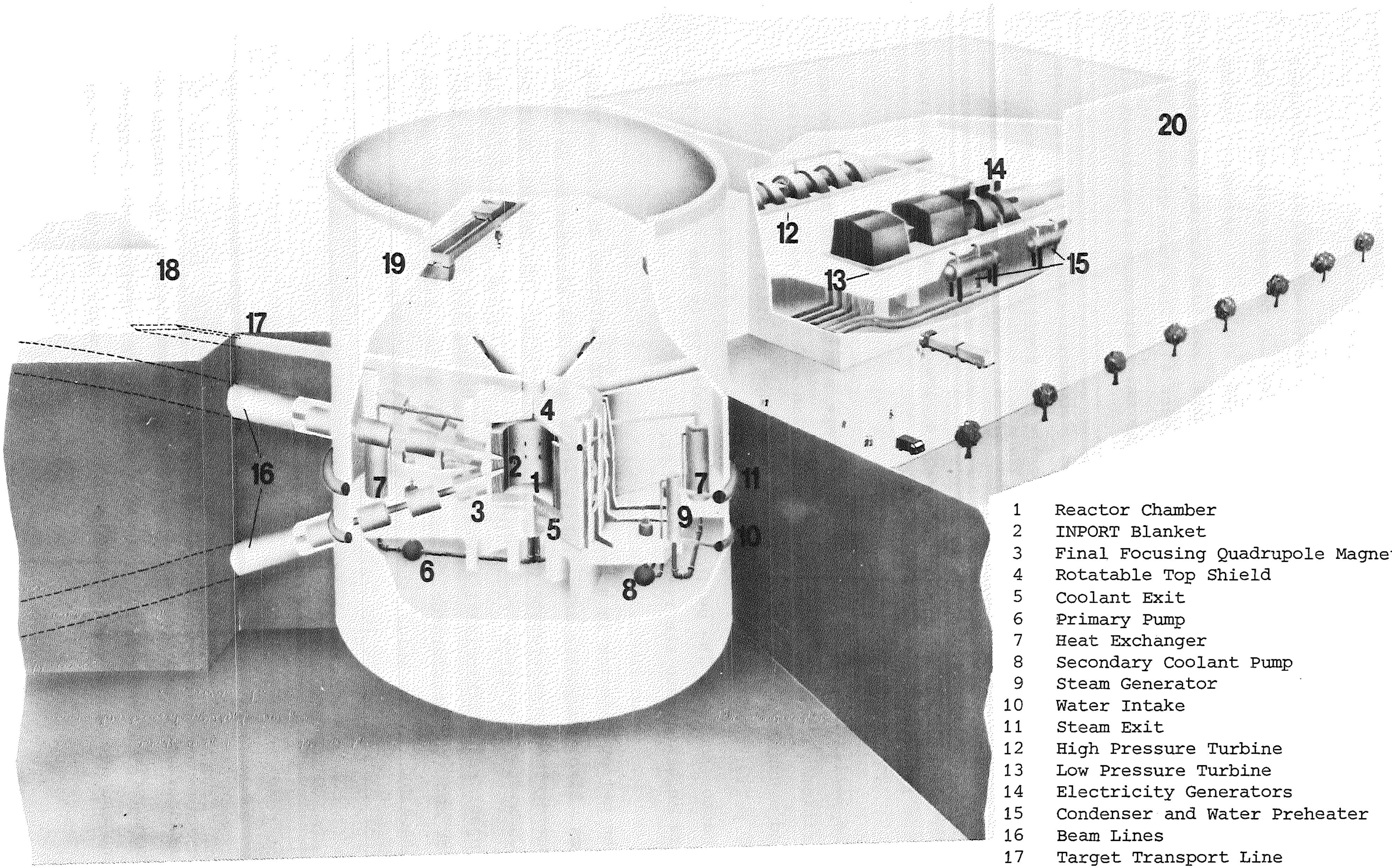


Fig. 4: HIBALL Reactor Building (940 MW_{el}) and Beam Lines

1 Reactor Chamber
2 INPORT Blanket
3 Final Focusing Quadrupole Magnets
4 Rotatable Top Shield
5 Coolant Exit
6 Primary Pump
7 Heat Exchanger
8 Secondary Coolant Pump
9 Steam Generator
10 Water Intake
11 Steam Exit
12 High Pressure Turbine
13 Low Pressure Turbine
14 Electricity Generators
15 Condenser and Water Preheater
16 Beam Lines
17 Target Transport Line
18 Target Factory
19 Reactor Containment
20 Machine Building

reactor chamber and push it through four intermediate heat exchangers (IHX) and back to the upper inlet ports of the reactor chamber. In the IHX the coolant ($Pb_{83}Li_{17}$) transfers its heat to a secondary sodium circuit with four secondary sodium pumps and four sodium heated H_2O steam generators and superheaters (Figure 4). The steam drives a turbine/generator system. The overall thermal efficiency is about 41%.

The beam lines, the primary and secondary coolant circuits are arranged in steel clad concrete walls. To avoid coolant/air reactions in case of leaks in pipes or other circuit components, these concrete cells can be filled with nitrogen. The whole reactor chamber is surrounded by a double containment with a low leak rate to minimize tritium releases into the environment.

The pellet factory contains the storage facilities for deuterium and tritium containers, the manufacturing line for the pellets, a tritium and deuterium filling station and a storage facility for the cryogenic DT pellets. Transport channels from the pellet factory lead to each reactor chamber. The pellets must be cooled up to the time when they are injected into the reactor chamber.

The pellet injector is a pneumatic gun using deuterium as a propelling gas. Electromagnetic accelerators are a possible alternative to this. During the acceleration process in the injector the pellet must be protected by a sabot from which it must be detached upon leaving the injector. Synchronisation of the pellet during its flight to the center and the accelerator beams is achieved by a laser light pellet tracking system which supplies the necessary signal to the driver rings releasing the ion beams [1, 2, 6].

RADIOACTIVE INVENTORIES OF HIF POWER PLANTS

Before one can adress the nuclear environmental and safety issues of any fission or fusion power plant one must list its inventory of radioactive material. Upon this basis, one can discuss the amount of radioactivity which might be released into the environment. Finally, one can determine the potential radiation exposure of the population in the immediate vicinity and at greater distance from the plant under normal operation and accident conditions.

Radioactive materials as they exist or are generated in different parts of the inertial confinement fusion reactor plant are:

- o tritium in the whole fuel cycle of the plant (target fabrication facility, breeding blanket, reactor cavity, vacuum pumps, clean-up and isotope separation systems),
- o activated debris material from burned pellets within the reactor cavity and in the vacuum system,
- o activated structural and shielding material around the reactor cavity (blanket, reflector, radiation shield),
- o coolant that is itself activated or contaminated with activated corrosion products,
- o activated structural and shielding material in the beam channels and at the focussing magnets,
- o activated and contaminated material which is being handled during maintenance, repair, and decommissioning.

In the following paragraphs the quantities of the different radioactive materials will be discussed. For tritium, we assume a closed cycle with constant inventory. For the other species, activities at shut-down after two years of full-power operation are given. At that time, the more important nuclides will have saturated and radioactivity build-up will continue at a slower rate.

TRITIUM INVENTORY

Within the reactor cavities of a HIF power plant the thermal power is generated by igniting and burning multilayer spherical targets containing about 4 mg of D-T. The shot frequency of a reactor cavity will be about 5 Hz for technical constraints explained in [1, 2]. At this frequency, one cavity is assumed to produce 1 GW of electrical power. This leads to a required tritium supply of about 1 kg/d in one reactor or about 4.1 kg/(GW_ed) for a power plant like HIBALL consisting of 4 reactors (1 kg of tritium has an activity of $0.96.10^7$ Ci). Only a fraction of about 30% or 0.3 kg/(GW_ed) of the tritium can be burned during the fusion process within the pellet. Thus, about 0.7 kg/(GW_ed) of unburned tritium must be handled by the exhaust and vacuum pump systems of each reactor cavity together with about 0.87 kg/(GW_ed) which will be continuously bred in the blankets (breeding ratio of 1.25). The solubility of tritium in the coolant and breeder material determines how much of it will remain in the cavity atmosphere and how much will enter the coolant. Due to the low solubility of tritium and deuterium in $Pb_{83}Li_{17}$ used as liquid breeder material and coolant at operating temperatures of 330-500^o and at 10^{-4} Torr vacuum conditions in the reactor cavity, most of the tritium generated by breeding will enter the cavity atmosphere. From there, it will flow to the exhaust processing system through large openings in the upper part of the reactor cavity together with the remaining deuterium, the ^4He produced by fusion, ^6He from the $^6Li(n,p)$ reaction, and some other impurities. The reactor cavity exhaust is pumped by compound cryopumps with an on-line time of about 2 hours and a tritium inventory of about 0.1 kg/GW_e. The compound cryopumps are regenerated so that helium is released first. Then, deuterium and tritium are released and sent to a clean-up unit where impurities are removed. The clean-up unit has a tritium inventory of only about 10 g/GW_e. The remaining deuterium and tritium is collected from all four reactor cavities and is finally separated in a cryogenic distillation unit (0.08 kg T inventory) to form a purified D-T stream for target manufacturing and a pure D_2 stream for the target injection system.

The amount of tritium to be stored in the target manufacturing station depends essentially upon the target manufacturing process and upon whether the filling of the targets will have to be done batchwise or in a continuous process. The number of targets to be produced will be about $3.2*10^5$ targets/(GW_ed). For the HIBALL plant with 4 cavities, this amounts to 1.3×10^6 per day (5.18 kg T). If the D-T fuel has to be filled into the targets by diffusion through the outer shells, the fill time will depend on the permeation rate of D-T through the lead and lithium-lead shells at sufficiently high temperatures. This may require up to several days and a coresponding D-T inventory within the target fabrication plant will be necessary. A continuous fill and fabrication process would require smaller D-T inventories. In this process, cryogenic spherical targets would be transported past sputtering guns which apply the consecutive spherical layers onto the spheres. At the same time they are cooled by a cold Helium gas jet [6].

TABLE 1: TRITIUM INVENTORY PER GW_e a)

Plant component	contributor	Tritium inventory kg/GW_e
Blanket	$Li_{17}Pb_{83}$ (coolant and breeder material	0.004
	Coolant guide tubes (SiC) in blanket section	0.003-0.255
Primary coolant circuits	$Li_{17}Pb_{85}$	0.119
Tritium cycle	Cryopumps	0.1
	Clean-up unit	0.01
	Isotope separation	0.02
Target fabrication	Targets (one full-power day supply)	1
	Storage in uranium beds	1
	Targets in fabrication b)	1 to 3

a) 1 kg corresponds to an activity of $0.96*10^7$ Ci

b) depending on target filling process

Table 1 summarizes the tritium inventories within a HIF reactor plant like HIBALL. By far the highest tritium inventory will occur in the target fabrication facility, where a one day supply of cryogenic targets to fuel the reactor cavities and a oneday tritium supply in uranium beds (prior to target filling) have been assumed.

The tritium inventory within the liquid blanket and breeder material $Pb_{83}Li_{17}$ will be relatively small (see Table 1). Due to the low solubility of only $7*10^{-2}$ wppm T in the coolant the tritium inventory amounts only to about 4 g/GW_e or $4*10^4 Ci/GW_e$. A similar inventory of 3 g/GW_e was assumed for the coolant guide structures (INPORT units) in the HIBALL study [2]. However, more recent estimates uncovered larger uncertainties of the tritium solubility in the SiC material of the INPORT structures. These estimates extend to as much as 255 g/GW_e [7]. The tritium inventory in the primary coolant circuits is estimated here to be 119 g/GW_e.

OTHER RADIOACTIVE INVENTORIES OF THE REACTOR CAVITY

Neutron induced activation of $Pb_{83}Li_{17}$ leads the radioactivity inventories as shown by Table 2.

TABLE 2: RADIOACTIVITY INVENTORY IN A REACTOR CAVITY DUE TO NEUTRON ACTIVATION OF PB

Isotope	Activity (Ci/GW_e)	Half life
^{203}Hg	$1.2*10^6$	47 d
^{205}Hg	$1.1*10^6$	5.2 min
^{204}Tl	$0.4*10^5$	3.78 y
^{203}Pb	$0.6*10^8$	52 h
^{205}Pb	$0.5*10^2$	15 000 000 y
^{210}Pb a)	$1.6*10^2$	138 d
Total	$6.2*10^7$	

a) from 40 atom-ppm Bi impurity

The highest activity with $0.6*10^8$ Ci/GW_e is represented by ^{203}Pb which has a half life of 52 h. Bismuth, a common natural impurity in lead, would be activated to ^{210}Po. In addition, radioactive corrosion products would have to be taken into account as radioactive materials. No data are presently available for these. In HIBALL, there is additional bismuth brought in by the ion beams; this amounts, however, to only 1 ppm in 30 full-power years assuming that it accumulates in the coolant [1, 2].

In addition, ^6He and ^8Li are produced from lithium. They contribute to the radioactive inventory of the operating plant but not to the release hazard because of their short half-lives of less than a second [1, 2].

RADIOACTIVITY FROM THE BURNING PELLET

The HIBALL pellet contains, besides D-T, only materials that are also present in the coolant (Li and Pb) and thus produces the same radioactive nuclides. Quantitatively, the pellet radioactivity adds a negligible amount to the coolant radioactivity.

RADIOACTIVITY AND AFTERHEAT IN THE REACTOR

Radioactivity will be induced by neutron capture in the structural material of the blanket, the first steel wall, the reflector, and shielding of the reactor. Calculations show that the buildup of radioactivity due to the short living isotopes will saturate after about 2 years operation. The total activity per unit of thermal power (Ci/Watt) for the whole reactor chamber (blanket, first wall and reflector) is shown in Figure 4. The radioactivity level at shutdown was estimated to be 0.6 Ci/Watt or $1.5*10^9 Ci/GW_e$. The bulk of this activity is due to neutron activation of steel structures. It decreases relatively slowly requiring about three weeks to be reduced by a factor of 10, and two years to be reduced by a factor of 100.

The heat power generated by the decay of radioactive isotopes immediately after reactor shutdown is 0.66% of the reactor power or

16.7 MW_{th} per reactor cavity. This requires a separate residual heat removal system. The afterheat decreases faster than the radioactivity [6].

The radioactivity in the shield is significantly lower than the radioactivity in the reflector. However, its value of $6.3*10^{-3}$ Ci/$Watt_{th}$ or $1.6*10^{7}$ Ci/GW_e is still significant. The afterheat at shutdown is 0.077 % of the operating power which corresponds to 1.9 MW_{th} per reactor chamber. Although this is relatively small it still will require a certain residual heat removal capacity [1, 2].

RADIOACTIVITY OF THE BEAM LINES

Neutrons from the burning pellet will stream through the beam ports up the beam lines and activate steel structures and shields there. The HIBALL-II final focussing layout [6] with its smaller beam ports and a final neutron dump about 40 m from the chamber wall constitutes an important enhancement over the original HIBALL design [1, 2], also with respect to activation. The activity per beam line was estimated at 66 Ci (corresponding to $1.4*10^{3}$ Ci/GW_e) for the new design. While this activity level is low compared to the one in the vicinity of the reactor cavity, it is still high enough to produce an unacceptable biological dose level [6, 8].

THE IMPORTANCE OF DIFFERENT RADIOACTIVE MATERIALS

The confinement of tritium within the reactor plant is one of the most difficult technical problems of HIF. Tritium permeates relatively easily through steel walls to the environment. Fortunately, the high inventory of about 12 kg T in the target factory of the HIBALL plant will be stored either at cryogenic temperatures within the pellets or safely absorbed in uranium beds. Only about 0.5 kg or $5*10^{6}$ Ci are in the coolant circuits or in the fuel cycle from where a fraction can permeate to the environment. Special design measures must be taken to prevent excessive tritium releases.

The ^{203}Pb activity of $2.4*10^8$Ci in the coolant of the whole HIBALL plant must be taken into consideration primarily in the accident analysis. A certain percentage of this radioactivity could reach the environment as aerosols. It can hardly be envisioned how major portions of the radioactivity accumulated in the blanket structures, the first wall, and the reflector structures could be released into the environment even in an accident. However, this radioactivity level will be important for considerations on remote handling and maintenance operations of blanket sections and for waste disposal questions.

TRITIUM RELEASE UNDER NORMAL OPERATION

INTRODUCTION

The permeation of tritium through the walls of steam generators and through components of the D-T fuel cycle represents the most important problem in the environmental safety of HIF-reactor plants. Gaseous ^6He has such a short half life that it does not play a role for radioactivity release in normal operation. All other radioactive materials (besides T) exist in either liquid or solid form within the plant and, hence, are not readily available for release. Tritium may be released as either T_2 or HT to the atmosphere or as HTO into rivers and lakes. Gaseous tritium is very soon oxidized into T_2 or HTO. Ultimately, any tritium escaping or released in a controlled manner will thus be present as tritiated water. Plants and animals then may contain HTO/H_2O ratios close to those existing in their environment. Radioactive exposure can occur from the ingestion of food or drinking water. Moreover, tritiated water can be absorbed by inhalation and through the skin of the human body. In this way, the ß-radiation (maximum energy 18 keV) of tritium causes a whole-body exposure.

PERMEABILITY OF TRITIUM INTO THE STEAM CYCLE

The permeation of tritium from the $Pb_{83}Li_{17}$ through the walls of the steam generators raises a difficult technical problem, as the permeability of tritium through steel and the heat transfer areas of steam generators are large enough so that considerable quantities of tritium can reach the steam cycle and the environment. If one assumes tritium permeabilities as given in the literature [1, 2, 9 ,10] and a heat transfer area of about 10^4 m^2 for a HIF reactor plant like HIBALL, one obtains a leakage rate of about 10^5 $Ci/(GW_e d)$. This is by a factor of about 10^3 higher than can be allowed. Therefore, a diffusion barrier of about 10^3 to 10^4 for tritium is needed, which can only be achieved by either double walled stem generators as they are developed presently for LMFBR applications or by an intermediate liquid metal circuit as presently applied in LMFBR's.

Double walled steam generators would have two tubes in close contact (Duplex tube design). On the inner side of these Duplex tubes, water or steam flows at high pressures (16 MPa), whereas on the outer side the $Pb_{83}Li_{17}$ coolant would flow across the bundles. A helium purge stream with some oxygen would pass along slots between the two tubes and

- o provide an oxidizing atmosphere between the two tubes,
- o carry tritium away which is permeating from the $Pb_{83}Li_{17}$ side into the space between the two tubes.

The oxide films formed between the two tubes and the oxide film on the water steam side would provide an additional effective diffusion barrier. The outer shells of the steam generators would also have to be double walled with a helium gas space satisfying similar conditions as in the Duplex tubes. Estimates summarized in the HIBALL study [2, 6] have shown that this diffusion barrier concept could be sufficient to keep the permeation of tritium into the steam cycle below about 5 $Ci/(GW_e d)$. However, experimental results would be needed to prove this concept.

If an intermediate liquid-metal loop according to standard LMFBR technique is employed instead of the Duplex steam generator, diffusion barriers of a quality of 10^3 are required to prevent excessive leakage of tritium into the intermediate circuit. A more recent design study [7] showed that eight intermediate heat exchangers and 24 sodium/water steam generators would be needed for HIBALL. The total losses of tritium from the intermediate circuits (with sodium as intermediate coolant) would then only be about 2 Ci/d. Only about 1 Ci/d would be released through the steam generator tubes into the water. The tritium inventory of the intermediate coolant loops would be less than 1 g [7].

The primary coolant circuits consisting of pumps, valves, pipings, flow meters, storage or hold-up tanks, purification systems etc. will have to be designed with aluminium sleeves to provide a secondary containment barrier against tritium permeation. Pumps, valves or similar components where leakages may occur will need additional jacketing or glove boxes to keep tritium leakages low.

Tritium leakages from the cryopump, clean-up and isotope separation systems are difficult to estimate. If one uses similar release rates as estimated for the Tritium Systems Test Assembly (TSTA) at Oak Ridge [11] and if one applies an adequate scaling up to a power plant like HIBALL, one obtains tritium release rates of 5 Ci/(GW_ed) [1, 2].

The chamber shielding and other auxiliary components will be water cooled. Small amounts of tritium will be generated there by neutron activation of deuterium or by tritium permeation from the blankets. Tritium losses from these systems are in the range of 1 Ci/(GW_ed).

The buildings in which tritium is handled will be equipped with a tritium recovery unit. In this unit, the tritium will be catalytically oxidized and then be absorbed on molecular sieves. Tritium losses due to building leakage are, therefore, expected to be small and in the range of 2 Ci/(GW_ed). As was discussed in "Tritium inventory" on page 9, the target factory will contain the largest portion of the tritium inventory. Most of this inventory will either be needed in the target filling process or be stored in uranium bed containers and in newly fabricated targets. The tritium leak rate from the target factory is difficult to estimate as no operating target factory exists. A loss rate of about 5 Ci/(GW_ed) of tritium from the target factory appears to be permissible. Table 3 summarizes the tritium losses from a HIF reactor plant like HIBALL. The total losses are estimated to be

22 (GW_ed). Of these total losses, 80 % are expected to go into the atmosphere and 20 % into water.

TABLE 3: TRITIUM RELEASED FROM A HIF PLANT
Electrical power: 3.8 GW_e

	Ci/(GW_ed)
Intermediate coolant circuit (sodium)	3
Double walled steam generators	5
Water coolant circuits of shield	1
Cryopump system	3
Fuel clean-up unit	2
Isotope separation unit	1
Target Factory	5
Buildings and tritium recovery system	2
Total release	22

TOXIC MATERIALS

In addition to the radioactive materials, there are also some toxic materials used in inertial confinement fusion reactor design. Such toxic materials are, e.g., mercury used in the vacuum pumps or the lead used as coolant ($Pb_{83}Li_{17}$) and as neutron multiplier. Although the potential hazards from these materials are by far smaller than those of radioactive materials, they will have to be considered.

ENERGY SOURCES

A significant difference between inertial confinement fusion reactors on one side and magnetic confinement fusion reactors as well as LMFBRs on the other is the energy which is stored within the central part of the plant and which is conceivably available for conversion into mechanical energy on short time scale to cause damage. In magnetic confinement fusion reactors, it is the internal energy of the plasma and the magnetic energy whose release within a few milliseconds is considered in disruption analysis. In LMFBRs, it is the thermal energy in tons of fuel which can potentially vaporize large quantities of the coolant up to high pressures if efficient mixing processes are assumed. Such energy resources are not available in inertial confinement fusion reactors.

CHEMICAL ENERGY AVAILABLE IN DEUTERIUM AND TRITIUM

As shown in Table 4, the HIBALL plant (with 3.8 GW_e) contains approximately 22 kg of deuterium and tritium in the target fabrication area. Total burn of this amount of hydrogen would produce about 1200-1400 MJ of energy However, the concern about hydrogen is not the total energy in a steady burn but rather the explosion potential. Hydrogen explosions are possible at concentrations above 4.1% in hydrogen-air mixtures. Techniques like compartment limitations, inert atmosphere and oxidization promoters (recombination) are well-established for minimizing if not eliminating the likelihood of explosions. As a reference, we note that after a meltdown of a water cooled fission power reactor about 1200 kg of hydrogen may be generated [12].

TABLE 4: TRITIUM AND DEUTERIUM INVENTORIES

component	tritium	deuterium kg/GW_e
Blanket	0.007	0.005
Tritium cycle	0.13	0.091
Target fabrication	2	1.4
Targets in fabrication	1-3	0.7-2

HEAT ENERGY IN THE FIRST WALL AND THE COOLANT SYSTEM

The Li-Pb in the first wall and the primary coolant system is a potential source for energy release in two respects:

- o chemical reactions with air, water and concrete are possible,
- o intimate mixing with water may generate high pressures due to rapid steam generation.

It is considered to be one of the great advantages of $Pb_{83}Li_{17}$ over other liquid metals that it is chemically much less aggressive, e.g., than sodium or lithium [13]. Thermal reactions with water, however, are a point of major concern in just the same way as for LMFBRs or MCF reactors. The principal technique to avoid the potential of large scale thermal reactions between Li-Pb and water is the provision of two walls between the two liquids. The double wall steam generator accounts for this requirement in the coolant cycle. However, the possibility of contact between the liquid metal coolant $Pb_{83}Li_{17}$ and the cooling water needs further consideration and research.

CONTAINMENT PHILOSOPHY AND REQUIREMENTS

The general safety philosophy applied to nuclear reactor design is to protect the environment from the radioactivity contained within the reactor chamber by several leak-tight barriers. In case of HIBALL, each reactor chamber produces a power of about 1 GW_e and contains a radioactivity inventory of

about 10^7 Ci Tritium,
about $6*10^7$ Ci in the coolant,
about $1.5*10^9$ Ci in structural material.

Although this is almost an order of magnitude less than the radioactive inventory of comparable converter reactors (LWR's) or breeder reactors (LMFBR's) [14, 15], it does not principally alleviate the requirements to be imposed on containment design. As the tritium inventory is by almost three orders of magnitude higher in fusion reactors, e.g., Tokamaks or ICF reactors as HIBALL, compared with fission converter and breeder reactors, this even increases the requirements for leak-tightness of the containment barrier.

The reactor chambers as well as the primary and the intermediate coolant circuits, must therefore be surrounded by an inner concrete containment, divided into steel lined cells each containing one of the three or four coolant circuits. Steel lining of the concrete cells is necessary to achieve the required high leak-tightness and to prevent reactions between the liquid metal coolant and the concrete in the case of leaks in pipings or valves. In addition, these inner concrete cells must be mainly filled with an inert atmosphere, e.g., 99% nitrogen and 1% oxygen in order to prevent PbLi fires or sodium fires (intermediate coolant circuits).

This inner containment must be surrounded by an outer containment which may be air filled but has to be designed to guarantee high leak-tightness, typically 0.25 volume%/day leak-rate as is the present standard technical requirement for LWR's [16]. The outer containment must be kept at a somewhat lower pressure against the environment so that air can only leak from the outside into the containment. The exhaust air of the outer containment is carried via filter systems into a stack and to the environment. Filter systems become necessary to retain aerosols which could develop in the case of chemical reactions of the liquid metal coolant (PbLi or sodium) with the oxygen in the containments.

The outer containment must also be equipped with a tritium removal system which consists of several catalytic recombiners, where tritium contained in the air is recombined with oxygen. The resulting T_2O can be extracted after cooling down in a heat exchanger, while cooler air is returned to the containment. Figure 4 shows the main components of such a containment system.

INTERNAL MISSILE PROTECTION

Missiles may be generated in a plant if energy can be converted rapidly into mechanical work. High pressure systems, such as pressurized water systems, provide this potential. The same applies to systems with high magnetic energy content or with two fluids (e.g., $Pb_{83}Li_{17}$

and water) which operate at significantly different temperatures in close neighborhood to each other.

With respect to the energy storage, inertial confinement fusion reactors differ considerably from both magnetic confinement reactors as well as LMFBRs. In fusion reactors based on magnetic confinement such as INTOR, the superconducting magnets represent a possible safety hazard in as much as the release of their stored energy (about 6 GJ per magnet) could conceivably serve as the initiating energy of an accident sequence that would release toxic or radioactive materials. In LMFBRs, it is the high temperature thermal energy of the fuel, which (in close neighbourhood to the liquid sodium coolant) represents a potential source for destructive mechanical work.

In a HIBALL type reactor, energy stored in magnets is significantly less important than in a TOKAMAK for instance. Near the reactor the beam focussing magnets can be of the normal conducting type (copper coils) and do not represent a major hazard potential for the reactor chamber.

Accidental hazards of superconducting magnets were extensively analysed [17]. According to this safety analysis, severe damage is only caused if a single-conductor failure within the winding would propagate to adjacent conductors. This can lead to a current arc which can destroy the magnet. If the entire winding and casing would rupture simultaneously at two different locations, the broken and loose section would become a missile accelerated by Lorentz forces [17].

Another issue is the energy stored in the magnet system of the accelerator, the storage rings and the beam channels. Consideration must be given to methods of localized uncontrolled release of this energy. However, because of the great distance from the reactors to the bulk of the driver system, failure of the driver system walls is of negligible importance with respect to activity release.

The other mechanism, which is generally considered as a potential source for missile generation, involves rapid conversion of thermal energy into mechanical work via mixing two liquids of significantly different temperatures. A requirement for work production is that the initially cold liquid should have a relatively low boiling point. In HIBALL, the water used for shield cooling may represent the cold liquid while the $Pb_{83}Li_{17}$ - or even some molten structural material produced in preceding sequences of accidental events - may be regarded as the hot liquid.

EXTERNAL MISSILE PROTECTION

External missiles may be generated from aircraft crashes, chemical explosions at or near the reactor site, or may result from other mechanically accelerated objects. Containment building design to accomodate such loadings and to avoid penetration of the containment barrier is standard practice for all nuclear reactors. HIBALL does not present any particular problems in this respect.

NATURAL DISASTERS

Natural disasters, such as earthquakes, floods and extreme wind loads, need similar consideration and analysis for inertial confinement fusion reactors as for other fusion and fission reactors. A safe shut-down of the plant and a reliable functioning of all afterheat removal systems must be guaranteed. One area in operational safety and reliability of the plant possibly requiring special treatment is the driver system. Because of its large spatial dimensions, preventive measures against flooding with water and the guarantee of proper geometrical alignment after earthquake loading will have to be investigated in more detail.

EVENTS CAUSED BY HUMAN INTERVENTION

Intentional human intervention as a cause of damage to the plant and as a potential danger to the containment system integrity is also a general concern for all kinds of nuclear reactors. The only reason why HIBALL may be considered more sensitive to such events is due to the larger site which includes the target manufacturing facility and the whole driver system. However, with adequate security measures taken, there is no indication of an increased hazard potential as compared to other reactor types.

ACCIDENT ANALYSIS

A first step in the assessment of safety and environmental effects for fusion power reactors is the identification of potential sources of hazard to the public's health and safety. Preliminary results of an attempt to identify hazardous materials for fusion reactor plant designs operating on the deuterium-tritium (D-T) fuel cycle are summarized in Table 5.

TABLE 5: LIST OF HAZARDOUS MATERIALS

Radioactive Materials	Toxic Materials
Tritium	Beryllium
Radioactive Coolant	Chromium (in structural components)
Radioactive corrosion products	Lead (coolant) Mercury (cryopumps)
Radioactive structural materials	

This listing is partly based on the analysis of TOKAMAK type fusion reactor plants [18] and takes also into account the somewhat different situation in inertial confinement fusion reactors. The non-radiological hazards (toxic materials release) appear to require some consideration because of the relatively large quantities in use or in inventory at the fusion power reactor site.

In addition to identification of these materials, there is the question of the source of that hazard; i.e. how is it released and/or made mobile if originally in solid form. There are several ways of identification of these sources. A preliminary listing is given in Table 6.

TABLE 6: SOURCES OF HAZARD FOR MCF AND ICF PLANTS

Material	Potential source of hazard
Hydrogen isotopes	Combustion; gross rupture of container;
Radioactive corrosion products	Fire; loss of coolant
Radioactive structural material (first wall)	Melting and vaporization; volatilization
Lithium, $Pb_{83}Li_{17}$	Fire; reactions between the liquid and steam, water, concrete
Mercury	Vaporization
Beryllium	Volatilization
Lead	Vaporization
Sodium (in an intermediate coolant cycle)	Fire; sodium/concrete reaction; sodium/steam reaction

Another method for categorization of accidents is the mechanism for activating the source of a hazard. One way is an attempt to classify accidents into two broad categories, (1) generic and (2) systems dependent. By "generic" it is meant that the accident is applicable to a wide range of designs. For example, a loss-of-coolant accident appears to be a generic accident, i.e., all designs have a coolant which could be conceivably lost.

Some of the generic hazard release mechanisms are:

1. Related to the D-T fusion reaction:
   a. plasma confinement instabilities (Tokamaks),
   b. localized plasma-wall reactions (Tokamaks),
   c. over-efficient micro explosions (HIBALL),
   d. overpower transients, power oscillations, time incoherences.
2. Related to components (Blanket, coolant system):
   a. loss of coolant,
   b. loss of coolant flow,
   c. afterheat removal failure,
   d. coolant fires and reaction with concrete,
   e. steam generator or secondary system failure.
3. Tritium fire or escape.

Another possibility to classify the accidents is given below. It is obvious that the various classifications overlap each other while emphasizing one particular aspect each.

1. Site-related accidents (earthquake, flood, tornado),
2. Missile Generation (external and internal),
3. Component failure (pumps, magnets),
4. Chemical reactions,
5. System over-pressurization,
6. Over-heating of the coolant system or pressurized containers,
7. Loss of off-site power,
8. Accidents in electrical systems (e.g., oil fire in a capacitor bank).

PRIMARY COOLANT SYSTEM ACCIDENTS

The total thermal power generated by HIBALL is 10233 MW to be produced in four reactor chambers. The coolant ($Pb_{83}Li_{17}$) will be operated in a temperature range from 330^{o} (inlet) to 500^{o} (outlet). The pressure in the blanket (i.e. in the SiC-tubes of the so-called INPORT units) is low since the coolant is essentially falling under gravity through the woven SiC tubes. As the reference design provides only very scarce information about the coolant system layout outside of the reactor cavity, we assume that the bulk of the coolant system is similar to the coolant systems of an LMFBR of similar size. In many respects, in particular regarding building design and major areas outside the reactor cavity and the primary cooling system, conventional fission reactor safety technology and safety standards will apply.

A preliminary investigation of the coolant system failures can concentrate on events which will be produced in the reactor chamber by such failures as:

- loss of coolant,
- loss of coolant flow,
- pressure pulses,
- coolant flow blockages,
- leaks and ruptures.

In the subsequent discussion we will disregard any active safety measures which would be installed to monitor the proper operation of the plant and initiate corrective actions (shut-down, emergency cooling) whenever the range of safe operation were exceeded. Credit will be taken from inherent mechanisms only.

LOSS OF COOLANT

In the event of total and instantaneous loss of coolant from a reactor, the evaporation-condensation heat transfer mechanism, which both protects the SiC-tubes from excessive heat loads and provides heat removal from the cavity, would become inoperable. The liquid $Pb_{83}Li_{17}$ would no longer protect the steel wall and shield from the radiation and energy release from the target. Further analysis of the thermal response and failure mechanisms of the SiC-tubes in the reactor cavity and of the power increase in the other parts will be necessary.

LOSS OF COOLANT FLOW

Loss of coolant flow through the blanket would cause the energy being dumped into the coolant to produce a rapid temperature increase. Two effects have to be considered:

- o subsequent loss of coolant from the blanket due to vaporization,
- o build-up of a $Pb_{83}Li_{17}$ vapor atmosphere in the cavity due to the lack of recondensation capability on the blanket tubes.

Whether this latter effect would soon enough and effectively inhibit the ion beams to reach the target and thus shut down the reactor, has to be investigated.

PRESSURE PULSES

Another question in this context is whether the evaporation of the coolant would give rise to pressure pulses of sufficient magnitude to affect the mechanical integrity of the coolant system.

Other potential sources of pressure pulses are:

- o shock waves produced by closure of isolation valves,
- o liquid-metal coolant/water interaction in the steam generator,
- o liquid-metal coolant/water interaction in the reactor chamber.

The first two causes can be eliminated with a coolant system design similar to LMFBR standards, that is: elimination of isolation valves in the coolant system and use of an intermediate coolant loop (the double wall steam generator proposed for HIBALL may provide a similar degree of reliability).

COOLANT FLOW BLOCKAGES

Coolant flow blockages are a point of concern. Partial blockages would cause the operating temperatures to be exceeded and possibly two-phase flow to be generated. The stability of such a flow needs more investigation. Total blockages would cause local vaporization, subsequent burn-out and likely failure of the corresponding INPORT unit. Monitoring the coolant flow (outlet temperature) of each coolant flow path individually is strongly recommended.

LEAKS AND RUPTURES

In the discussion of coolant system ruptures, we must distinguish between those leaks which cause loss of liquid from the coolant system, and others which cause undesired by-passes but without integral loss of material from the system. Leaks out of the system present a potential activity realease mechanism and may cause coolant freezing in areas where it may have considerable effect on later repair operations. For preventing and monitoring such leaks, the same techniques as in LMFBRs apply, up to and including double wall design in inaccessible areas.

Leaks within the coolant system do not immediately present a potential for activity release. However, they cause the coolant flow to concentrate in areas wheres it is not expected, and cause reduction of cooling capability in areas where such reduction may lead to damage. An example of this type of leak is the failure of an INPORT unit inside the reactor cavity. Significant difficulties in detecting such failures are envisaged. As a precaution, monitoring the outlet temperature (if not the flow rate itself) of each INPORT tube individually will have to be considered.

FAILURE OF THE FUELING SYSTEM

Failure of the fueling system to deliver the target into the center of the cavity on time have two major safety aspects:

1. shine-through of the ion beams,
2. pellet impact on the opposite first wall.

The first aspect will be discussed in the next chapter. The second aspect indicates an advantage of the HIBALL-type design (with vertical pellet injection) over a design which would inject the pellet horizontally: the pellet would be dumped into the pool on the bottom of the cavity and would be absorbed there.

BEAM POINTING OR TARGET DELIVERY FAILURES

In magnetic confinement fusion reactors, the penetration of neutral beams (used for heating) through the plasma is an area of major concern. A similar situation would arise if an ion beam in HIBALL would hit the opposite wall instead of the target. According to recent new evaluations of the final focussing system for the ion beams, the beams have 20 cm radius at 8 m from the cavity center. Assuming that the convergence and divergence of the beam occurs symmetrically along the path through the cavity, the beam - unless stopped by the target - would illuminate a circular spot of 12.5 cm radius at the first wall surface. The average energy density in this hot spot is 5.1 MJ/m^2 per shot for a beam energy of 0.25 MJ. At normal operation, the energy deposition at the first wall surface (assuming 87 MJ of X-ray energy according to Fig. VI.4-2 in [2]) is 0.28 MJ/m^2 per shot. Hence, the non-absorbed ion beam produces a load that is at least 18 times higher than during normal operation.

According to [2, page 144], a target micro-explosion causes the evaporation of approximately 4 µm from the liquid first wall surface. Thus, provided that the surface can be rewetted sufficiently will within the time period of 0.2 seconds, the energy sink capability appears to be adequate for the full ion beam load. However, the structural response caused by the thrust of the evaporated layer will require more detailed considerations.

Alternative design solutions may be considered for the beam shine-through areas:

1. Symmetrical layout of the beam entrances such that they face each other pairwise.
   In this case, the ion beam would penetrate backwards into the opposite beam line. This may provide a method to dump the energy over larger areas. However, it would likely complicate the design of the beam lines as well as their control system.

2. Provision of special beam dumps.

By tilting the surface with respect to the centerline of the beam, the geometry can provide significant reduction of the beam intensity. This technique is commonly used for dumping the power of high energy beams. However, for the extreme heat loads envisaged here, this approach will not provide sufficient benefits over its disadvantage effects of disturbing the overall first wall geometry.

In the above estimates, no credit was taken from the fact that the high concentration of ions in the cavity center (in particular if all beams meet simultaneously) will likely cause the beams to diverge due to space charge effects. This aspect needs further investigation.

A separate issue is the behaviour of a target which is only partially and unsymmetrically illuminated by ion beams. The unsymmetrical reaction would cause the target to become a missile which has to be considered as a potential loading for the first wall and the roof. The bottom is inherently protected by the coolant pool.

CRYOGENIC SYSTEM FAILURES

Failures of the cryogenic system have to be considered with respect to the following potential consequences:

1. Failure of cooling of the superconducting magnets with subsequent release of the magnetic energy resulting in mechanical forces able to perform destructive work. This chain of events is much less severe in HIBALL than in an INTOR-type reactor, e.g., because HIBALL has much smaller superconducting coils.
2. Evaporation of the cryogenic liquids (He and N_2) leading to pressure build-up in the containment building. Again, this problem is less severe than in a TOKAMAK reactor of similar size because of the smaller amounts of cryogenic fluids available.
3. Subcooling of structural components inducing thermal stress while at the same time causing embrittlement of the material. Such sequences of events would have to be studied in more detail in

later design stages, but no fundamental difficulties in dealing with this problem are envisaged.

4. Explosive vaporization of cryogenic liquid upon contact with a hotter fluid like water or lead-lithium. Here again, more design details are required to analyze this possibility properly on the basis of plausible mechanisms for such an event. Also for TOKAMAK type reactors, this possibility should be investigated more intensively.

HYDROGEN FIRES

As discussed already in "Chemical Energy Available in deuterium and tritium" on page 19 and shown by Table 4 most of the deuterium and tritium will be stored in the target fabrication area. Leaks in storage facilities and pressurized containers could lead to air-deuterium or air-tritium mixtures having the potential of explosions if hydrogen concentrations above 4.1% are attained. Application of inert gas atmospheres will decrease the potential of explosions somewhat by increasing the lower limit for the critical concentration. More effective means will be double containment for pressurized containers and storage facilities as well as the application of hydrogen recombination devices in areas where leaks might develop.

EVENTS EXTERNAL TO THE FACILITY

Events external to the facility fall into three categories:

1. natural disasters (earth-quakes, strong winds and floods),
2. aircraft crashes,
3. gas cloud explosions and
4. events caused by intentional human intervention.

The first category has been briefly discussed in "Natural Disasters" on page 23. All these events, however, do not present any particular problem for an inertial confinement fusion reactor which is qualitatively different from the case of a magnetic confinement fusion reactor or an LMFBR. It would be much too early to undertake a quantitative risk assessment. In such a later assessment, two aspect would have to be considered in more detail:

1. the effect of combining the power plant together with the reprocessing and fuel pellet manufacturing plant on one site, and
2. the large area of the site (about 2 by 2 km, with an appendix of about 3 km by 500 m for the linear accelerator) which makes it more susceptible to any kind of external event.

INCIDENTS DURING MAINTENANCE OPERATIONS

A preliminary investigation of fusion power plants (both with magnetic confinement and inertial confinement) has indicated that maintenance operations play a dominant role. They are perhaps more liable for activity release than the periods of power production. This is due to the inherent fact that many and sometimes large activated and contaminated structural components have to be handled (inspected, disassembled, transported, repaired, reassembled) remotely. However, because of the complexity of these operations and the lacking experience with them, it is much too early to give a quantitative assessment of their influence upon the activity release potential. Instead, it appears to be a safety requirement for the design of all maintenance operations that their contribution to the activity release should not be greater than if the plant were producing power during the shut-down time instead of being maintained. This criterion should include incidents like dropping a piece of equipment, imperfect closure of containment vaults or failure of welding or cutting machinery.

HUMAN ERRORS

Human errors have to be considered as potential origins for sequences of events which may finally lead to activity release. Human errors may also be of concern with respect to safety if a person's reaction is part of the whole set of countermeasures against a technically originated incident.

During normal operation (that is: during power production) we can expect that the well established standards of fission reactor safety technology will also apply for fusion reactors, e.g.:

- o the plant will be guarded against potentially hazardous human actions by appropriate active and passive safety measures,
- o no human intervention is required within 30 minutes after a potentially hazardous incident to ensure plant safety.

Much more consideration will have to be given to human errors and their potential consequences during maintenance. However, the maintenance operations will have to be defined in considerable detail before such an analysis can produce useful results.

ENVIRONMENTAL ANALYSIS

TRITIUM RELEASE DURING NORMAL OPERATION

With a given release rate as estimated in Table 3 the exposure dose rate due to normal operation can be calculated for a given distance from the reactor plant. Assumptions must be made for the exhaust stack height, the atmospheric dispersion of the radioactivity and the population density around the plant. On the basis of a 100 or 200 m high stack for tritium release, metereological conditions as measured at Hannover, FRG, and a population density of 250 persons/km^2 the resulting exposure dose rates were calculated following the national German guide-lines GMBI-21 [19]. Figure 5 shows the local effective committed exposure due to gaseous and liquid effluents. It also compares the exposure doses on a 1 GW_ea basis for a pressurized water reactor (PWR) and the respective reprocessing plant with a HIBALL-type plant. The higher stack of 200 m of the latter strongly influences the committed local exposures in the direct vicinity of the plant. Whereas the HIBALL reactor plant will release only tritium, additional radioactive nuclides, e.g., radioactive noble gases (krypton, xenon) and β- or α-emitting aerosols (fission products and actinides) must be accounted for in the case of the PWR and its reprocessing plant [20, 21]. All exposure dose data decrease strongly with distance from the plant and are in the range of 0.1 µSv/(GW_ea) or 0.01 mrem/(GW_ea) at a distance of 10 km from the plant. This is well below the present limits imposed by radiation protection ordinances.

For a 5 GW_e HIBALL-type plant in which 5 reactors of 1 GW_e each would be driven by one linear accelerator at a plant load factor of 0.7, the dose rates would be very close to those of the PWR reprocessing plant scaled to 1 GW_e. In making such comparisons, however, it should be recalled that the results for a PWR and its respective reprocessing plant are based on realistic (measured) data whereas the estimates for a HIF plant depend upon the assumptions made for the diffusion barriers in the steam generator tubes and other permeation rates of tritium in different parts of the plant.

A comparison of tritium releases from fission reactors and their fuel cycle shows that, under the present assumptions, reprocessing plants and heavy-water reactors would have similar releases per GW_ea as ICF or MCF reactor design concepts (Table 7). Again it must be emphasized that the releases of tritium from fusion reactor plants are only preliminary estimates which may give an indication for confinement measures to be designed into such future plants. In this sense the difference in release rates between HIBALL and STARFIRE stems only from differences in assumptions.

ACCIDENTAL RELEASES OF RADIOACTIVITY

Licensing regulations will require the consequence analysis of radioactivity releases from the reactor plant to the environment. This analysis would have to be performed following through all possible accident sequences which can lead to major radioactivity releases from the plant. As an example, two such accident sequences are briefly described.

- As a consequence of an earthquake a stress induced leak in one or several beam channels close to the reactor could develop. Air could flow into the cavity and through chemical reaction of oxygen

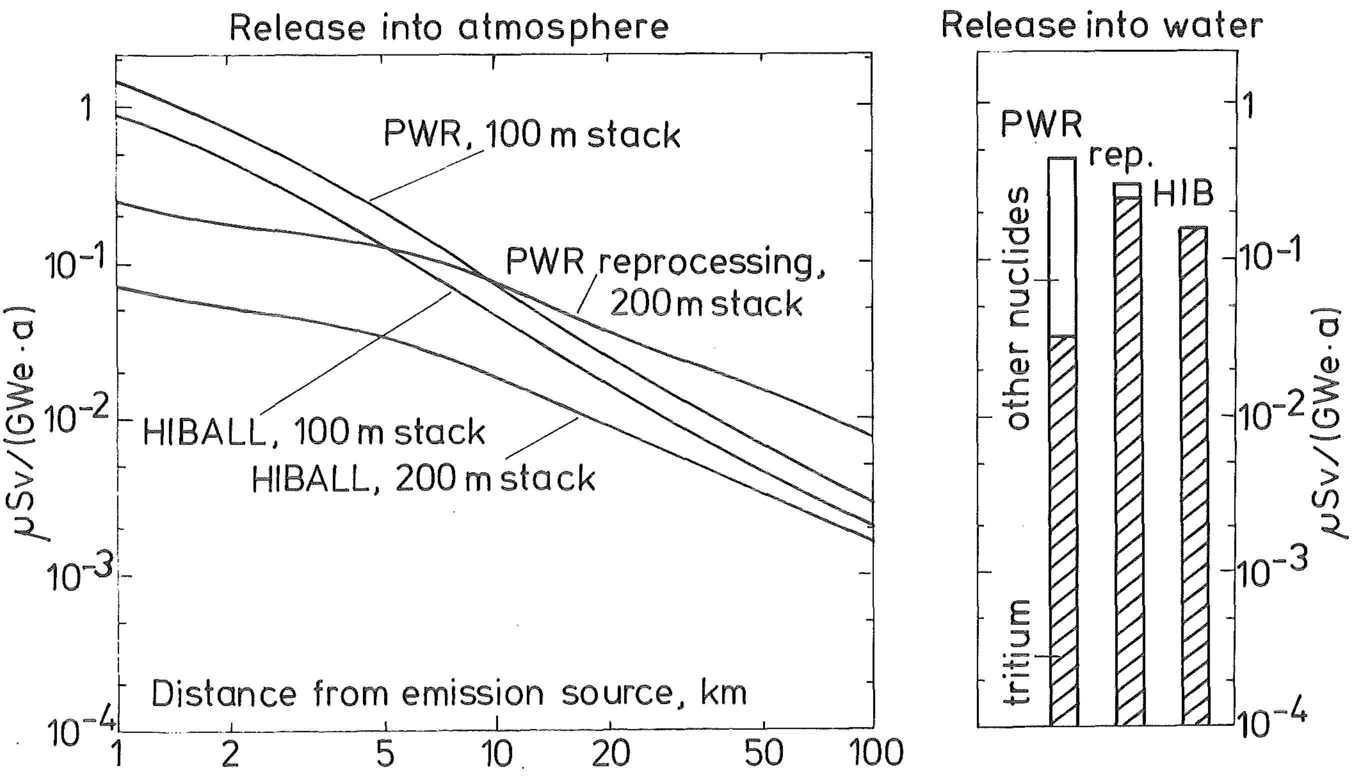


Figure 5. Comparison of committed exposures: The local effective committed exposure due to gaseous and liquid effluents of HIBALL is compared with a PWR and a PWR reprocessing plant.

with $Pb_{83}Li_{17}$ a certain amount of aerosols would be generated. The cryopumps may be heated up and release their tritium inventory. Both lead-lithium oxide aerosols and tritium would flow into the outer containment of the reactor or directly into the environment, depending upon where the leak develops.

- Loss of cryogenic heat sinks in the target manufacturing and storage facility may occur as a consequence of fire which also may damage the containment. Tritium may be released and penetrate through leaks to the environment.

These are only two examples of accident sequences possibly leading to major releases of tritium and radioactive aerosols. As a detailed fol-

TABLE 7: TRITIUM RELEASE RATES FROM FISSION AND FUSION REACTOR PLANTS

	Gaseous $Ci/(GW_e a)$	Liquid $Ci/(GW_e a)$
Pressurized Light Water Reactor (PWR)	45	400
Reprocessing for PWR	1100	3300
Heavy Water Reactor (HWR)	15000	7500
HIBALL (ICF)	5800	1500
STARFIRE (Tokamak)	3200	800

low-up of a whole spectrum of accidents is not possible at the present stage of conceptual plant design, we consider a single typical case instead. We assume that 0.5 kg tritium ($5*10^6$ Ci) plus 1% of the coolant activity (see Table 7) would be suddenly released during an undefined severe accident. This puff release is assumed to occur from one of the 1 GW_e power reactor units of a multiple-unit HIF reactor plant. This assumption is not based on a deterministic analysis but rather represents a postulated conservative upper bound source term for radioactivity entering the environment. More realistic analysis may lead to substantially lower releases.

EXPOSURE DOSES FROM ACCIDENTAL RELEASES

The cumulative radiation dose from a puff release of radioactivity some person receives at a certain distance from the reactor plant depends on the release height and on the meteorological conditions, e.g., wind speed, wind direction and atmospheric dispersion rate. Cumulative doses were calculated for the above activity released at a height of 100 m in two different weather situations. The exposure pathways considered were external exposure from the plume, external exposure from the ground, internal exposure via inhalation and internal exposure via ingestion of agricultural products harvested and consumed immediately after the accident. For dispersion category C (slightly unstable atmospheric conditions, v = 3 m/s at H = 10 m, no rain) the maximum dose is received at a distance of 500 m downwind from the exhaust stack and amounts to 105 mSv or 10.5 rem. For dispersion category F (inversion, v = 2 m/s at H = 10 m, no rain) the maximum is found 8 km from the plant and amounts to 2.1 mSv or 0.21 rem.

Calculations for a 0.5 kg tritium release were also made assuming zero release height, i.e. direct leakage from a building. In this case, the maximum dose is received very close to the plant. The dose at a distance of 1 km is 360 mSv or 36 rem in inversion-type weather but only 40 mSv or 4 rem with a slightly unstable atmosphere.

It can be concluded that for these releases the exposure would remain below 250 mSv (25 rem) at a distance of 2 km from the plant even in unfavorable weather conditions. A 2 km exclusion area boundary is roughly consistent with the extension of a complete HIBALL power plant including the driver. The assumed releases thus stay below the 25 rem dose limit of U.S. federal regulations 10 CFR 100 and below the TFTR dose criterion for an accident with a probability of occurrence of 10^{-7} per year which is also defined as 25 rem at the plant exclusion area boundary.

SITING ASPECTS

With respect to the site selection, a HIBALL type power plant has similar requirements as any other nuclear power plant of the same power level.In particular, the safety requirements for the site appear to be the same. Only with respect to the needed area of land a remarkable difference can be noticed: the additional area requirement for the driver system (especially for the linear accelerator several km long).

ACKNOWLEDGEMENT

The authors wish to express their sincere appreciation for the support which they received from Dr. von Möllendorff, Institut für Neutonenphysik und Reaktortechnik, in discussions and during the final preparations of this manuscript.

REFERENCES

[1] B. Badger et al.: HIBALL - A Conceptual Heavy Ion Beam Driven Fusion Reactor Study. Volume 1. KfK 3202/1, UWFDM-450, Kernforschungszentrum Karlsruhe (1981).

[2] B. Badger et al.: HIBALL - A Conceptual Heavy Ion Beam Driven Fusion Reactor Study. Volume 2. KfK 3202/2, UWFDM-450, Kernforschungszentrum Karlsruhe (1981).

[3] -: International Tokamak Reactor (INTOR): Phase One. IAEA, Vienna, 1982. STI/PUB/619; ISBN 92-0-131082-X. Karlsruhe (1981).

[4] R.L. Woerner, H. Rieger: Fabrication and characterization of cryogenic targets for inertial-confinement fusion. University of California Report UCRL-15113 (1980).

[5] G.L. Kulcinski et al.: The INPORT Concept - An improved method to protect ICF reactor first walls. UWFDM-426, August 1981.

[6] B. Badger et al.: HIBALL-II, An Improved Conceptual Heavy Ion Beam Driven Fusion Reactor Study. KfK 3840, Kernforschungszentrum Karlsruhe, to appear.

[7] H. Runge: Tritium-Bilanz und Verträglichkeit von SiC mit $Li_{17}Pb_{83}$ für das Fusionsreaktorsystem HIBALL. Report INTAT 55.06775.6. Interatom, Bergisch-Gladbach (Februar 1984).

[8] M.E. Sawan, W.F. Vogelsang and D.K. Sze: Trans. Am. Soc. 39 (1981) 777.

[9] T.A. Renner, D.J. Rave: Tritium permeation through Fe-2 1/4 Cr-1 Mo steam generator material. Nuclear Technology 4 (1979) 312-319.

[10] J.T. Bell et al.: Tritium permeability of structural materials and surface effects on permeation rates. Proc. on Tritium Tech-

nology in Fission, Fusion and Isotopic Applications, ANS Topical Meeting, US-DOE Report CONF-800427 (1980) 48-53.

[11] J.L. Anderson, R.H. Sherman: Tritium systems Test Assembly. LA-6855-P (1977).

[12] S. Dorner, G. Schumacher: Personal communication (1984).

[13] L. Muhlestein et al.: Summary of HEDL fusion reactor safety support studies. HEDL-SA-2360ß (1984).

[14] G. Kessler: Nuclear Fission Reactors. Springer-Verlag, Wien (1983).

[15] W. Häfele et al.: Fusion and Fast Breeder Reactors. International Institute for Applied Systems Analysis, Laxenburg Austria, RR-77-8 (1977).

[16] W. Braun et al.: The reactor containment of German PWR's of standard design. Int. Conf. on Containment Design, June 17-20, 1984, Toronto, Ontario.

[17] F. Arendt, P. Komarek: Potential failures and hazards in superconducting magnet systems for fusion reactors. Nuclear Technology/Fusion, Vol. 1 (October 1981) 552.

[18] W. E. Kastenberg, D. Okrent: Some Safety Considerations for Conceptual Tokamak Fusion Power Reactors. Report ER-546, Research Project 236-1. Univ. of California, Los Angeles (July 1978).

[19] Bundesministerium des Inneren, Bundesrepublik Deutschland: Allgemeine Berechnungsgrundlage für die Strahlenexposition bei radioaktiven Ableitungen mit der Abluft oder in Oberflächengewässer. Gemeinsames Ministerialblatt 21 (August 1979) 369-436.

[20] G. Halbritter, E. Lessmann: Vergleich der Strahlenexposition aus Emissionen von Modell-Brennstoffkreisläufen für den Druckwasserreaktor und den Schnellen Brutreaktor. Kernforschungszentrum Karlsruhe, Report KfK 3315 (1982).

[21] E. Lessmann: Personal communication (1983).

[22] A. Bayer: Personal communication (1983).