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HYBRID REACTOR SAFETY STUDY

ANNUAL REPORT

OCTOBER 1, 1978 - SEPTEMBER 30, 1979

by
PROJECT STAFF

Prepared under
Contract DE-AT03-76ET51011
for the San Francisco Operations Office
Department of Energy

DECEMBER 1979

GENERAL ATOMIC COMPANY

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GENERAL ATOMIC COMPANY

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ABSTRACT

A preliminary generic safety evaluation of the fusion-fission hybrid reactor concept has been performed and a hybrid reactor safety program plan for guiding future safety work has been proposed. The emphasis of the work was limited to accident analysis where the main concern is for the health and safety of the public. Major radioactive sources in the hybrid were identified and their inventories compared to those of fission reactors. The means for accidental release of radioactivity to the public were identified, as were the barriers which preclude such accidental releases. Consequence analyses of hypothetical bounding accidents potentially defining the upper bound envelope of risk/consequence to the population and environment surrounding the hybrid site were performed.

The FY79 effort was primarily a preliminary survey of safety issues upon which to base the proposed Hybrid Safety Program Plan. The methodology of probabilistic risk assessment (PRA) was selected as being a valuable technique to use to evaluate the safety aspects of the hybrid reactor and to provide guidance in safety research and design development efforts. The Program Plan calls for consideration of safety issues from the very start of hybrid design and use of guidance from the safety studies to direct hybrid development efforts. This is sure to lead to a safer reactor plant in the end, having made safety an integral part of hybrid reactor design. The Hybrid Safety Program will serve as a framework guiding safety related activities beginning with preconceptual design and continue through eventual demonstrations and commercialization of fusion-fission hybrid concepts.

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1. INTRODUCTION AND SUMMARY

This report is the result of a preliminary assessment of the safety aspects of the fusion-fission hybrid reactor concept done during 1979 by General Atomic Company for the U.S. Department of Energy, Office of Fusion Energy. There is a wide spectrum of possible roles, operating modes and design options potentially available to the hybrid reactor concept. Because of increasing public awareness of the importance of nuclear power system safety, it is highly appropriate that the safety aspects of the various hybrid designs be considered at an early stage in the development of the hybrid concept. The intent of this on-going hybrid reactor safety study is to investigate safety aspects at the pre-conceptual design stage, to develop a hybrid safety program plan that will focus on evaluation of the important safety issues and to thus offer guidance from the safety point of view on the design choices to be made during the process of development of the hybrid reactor concept.

1.1 SCOPE OF WORK

The scope of work for FY79 was to perform a preliminary generic safety evaluation of the fusion-fission hybrid reactor concept and to propose a hybrid reactor safety program plan for guiding future safety work. Since the fusion-fission hybrid reactor is still in the early conceptual design phase, the emphasis of the work has been limited to accident safety analysis where the main concern is for the health and safety of the public. Occupational and routine hazards from operation of a hybrid reactor are not to be ignored but these facets of safety can be deferred until the design of the hybrid reactor is developed further.

A safety program can take a number of directions. The methodology of probabilistic risk analysis has been selected as being the most appropriate technique to use to evaluate the safety of the hybrid reactor. This methodology is particularly well suited to assessing safety during the conceptual design phase when design details are not well defined. Probabilistic risk analysis can be utilized as an adjunct to the design effort in order to provide guidance as to the direction the hybrid reactor design should take as, for example, in determining relative safety merits of different design options. At the present time there is no firm consensus in the hybrid design community as to the appropriate role, configuration or design of a hybrid reactor (1.1). Designs have been proposed that produce energy or fissile fuel as the sole product as well as systems that produce both. Use of both uranium/plutonium and thorium/uranium fuel cycles have been suggested, as well as the application of both cycles in a single design. A wide variety of fusion drivers could be employed and blanket designs based on all known fission reactor technologies are possible. As the hybrid reactor concept advances and choices are made amongst this myriad of design possibilities, it is important that the safety aspects of the various design options and the safety implications of the design choices be included in the decision process. Probabilistic risk analysis can help in the quantification of the safety considerations of the design choices.

Probabilistic risk assessment is also well suited to evaluating where the hybrid reactor may have safety weaknesses and to provide the guidance necessary to direct safety research and development efforts. Finally, because it is possible with probabilistic risk assessment to consider safety issues from the very start of the hybrid development, it is sure to lead to a safer reactor plant in the end, having made safety an integral part of the hybrid reactor development effort.

1.2 HYBRID SAFETY PROGRAM PLAN

The objective of the Hybrid Safety Program is to insure development of hybrid reactor designs that exhibit acceptably and demonstrably low public risk. The Hybrid Safety Program will serve as a framework guiding safety

related activities beginning with preconceptual design and continuing through eventual demonstration and commercialization of the now emerging fusion-fission hybrid concepts. The Hybrid Safety Program plan developed to accomplish this objective is described in Section 6 and summarized briefly below.

It is the intent of the Hybrid Safety Program to identify the similarities and differences between the safety-related characteristics of hybrid reactors and those of fission or pure fusion systems alone. This will allow the Hybrid Safety Program to focus on those aspects that are unique and will allow maximum use to be made of the work being done as part of the much larger fission safety program and fusion safety program.

Of necessity, the hybrid safety program plan has been divided into two phases. The first phase, Phase I, defines the safety activities associated with conceptual design, identifies major accident contributors and provides preliminary design option guidance. The second phase, Phase II provides further definition of safety activities as the hybrid design matures into detailed designs. Current safety program emphasis will be placed on Phase I concerns.

1.2.1 Phase I - Conceptual Design Phase

This phase is broad in scope and its objective is to provide definition, guidance and coordination during the pre-conceptual design phase of the hybrid reactor development program. On the basis of the preliminary hybrid safety survey done during FY79, Phase I will attempt to offer quantitative design guidance so that the safety characteristics of the hybrid concept are maximized as conceptual designs evolve. The initial step in Phase I will be to consider generic issues that will be applicable to the hybrid concept regardless of the specific design.

- The safety aspects of the basic blanket concepts (energy producing, fast-fission fuel and energy producing, and fission-suppressed fuel

producing) must be generically compared in a quantitative manner so that safety considerations can be fully considered in the selection of the desired hybrid reactor operating mode.

- The difference between uranium-based and thorium-based hybrid blanket hazard potentials, accident pathways and probabilities must be quantified.
- The relative importance of tritium to the safety evaluation of hybrid reactor systems must be assessed. It is possible that tritium could be a significant risk contributor through low consequence, high probability accidents. This needs to be more fully assessed and the safety-related design of tritium systems needs to be optimized. It is expected that the tritium systems of hybrid reactors will be very similar to those of pure fusion reactors. As a consequence, this aspect should be closely coordinated with the pure fusion safety program.

These initial steps in Phase I will allow quantitative inclusion of safety considerations in the generic design decisions that must be made to direct the hybrid reactor program.

The second series of steps in Phase I will be less generic and more design-specific. Conceptual designs must be examined, safety assessment made and safety-related design recommendations suggested. Several items should specifically be included as they may have unique aspects for the hybrid.

- Coupled fusion-fission events must be considered. Fusion system component failures that can cause fission blanket-related accidents and fission blanket accidents that can cause release of the radioactive inventories associated with the fusion components must be investigated.

- Radioactivity barriers must be investigated for the specific designs. Design optimization of these barriers at the pre-conceptual design stage may allow selection of reactor concepts that have favorable safety features for further development.
- Accident mitigation systems must be considered for the various conceptual designs. These systems may have significant impact on the cost of a hybrid reactor, as they do on that of fission reactors, and the requirements for such systems must be carefully assessed.

The focus of this phase of the program will be to accomplish necessary safety-related definition studies, perform preliminary safety analysis and to offer design guidance input to emerging hybrid concepts.

Definition Studies Task

This task will define the objectives of the overall safety program plan and monitor the conduct of the elements of the plan toward satisfying these objectives.

Preliminary Safety Analysis Task

This task will develop and employ systematic methods for the identification, evaluation and cataloging of the main accident-initiating events of a given conceptual hybrid design. Once the initiating events have been isolated, the response of the hybrid design to these initiators will be assessed and event sequences will be constructed. The hybrid's hazardous materials, particularly the radioactive inventories, will be cataloged and effective barriers to prevent their release will be listed. Event sequences sufficient to breach these barriers are of particular interest and will be examined by preliminary consequence analysis and risk evaluations.

The sequence probability estimates along with preliminary consequence analysis results will initially be used to rank the safety importance of events in a preliminary risk evaluation.

Design Guidance Task

This task will provide design guidance in the emerging hybrid reactor design(s). Earlier preliminary safety analysis work on bounding and "typical" accident consideration will be refined.

Preliminary Probabilistic Risk Assessment (PRA) will be performed on the candidate hybrid designs. These risk assessments will then be applied in the systematic comparison of safety related concerns in the hybrid program. Comparisons and recommendations will then be based on a quantifiable risk analysis basis.

1.2.2 Phase II - Detailed Design

Phase II of the safety program begins when preliminary and final design begins on the hybrid reactor. Phase II of the program is meant to deal with safety issues through the licensing process. Since it is impossible to predict the direction in which the hybrid reactor program will develop, it is best to outline a long range safety program that will be general and adaptable to changing conditions.

The safety program plan for Phase II is divided into eight task areas described below. The tasks are functional in nature but as the program progresses it may be more appropriate to change from functional tasks to ones that are more system and component oriented.

Definition Studies

This task is used to lay the foundation for specific efforts under the remaining tasks and to guide the course of the overall safety program.

Data Base

This task collects and organizes the data necessary to complete the remaining tasks.

Methods Development

This task develops the calculational models and methods necessary for performing the analytical tasks.

Deterministic/Consequence Analysis

The analysis of accident sequence including plant response, release of radioactivity into the environment, dispersion of radioactivity in the atmosphere and health effects will be done under this task.

Probabilistic Analysis

The probabilistic aspects of accident sequences will be evaluated under this task.

Testing Program

The effort to define, monitor and evaluate the experimental effort to verify safety adequacy and to determine reliability will be conducted under this task.

Design Review

This task defines the activities for organizing and providing the review of the evolving hybrid design to ensure that necessary modifications to task area work are accomplished.

1.3 SUMMARY OF FY79 HYBRID SAFETY STUDY

The work performed during FY79 is primarily a preliminary safety survey of the fusion-fission hybrid reactor upon which to base the proposed hybrid safety program plan. Several conclusions can be made as a result of the safety survey:

- For the reference fast-fission breeding blanket systems, the fission product inventory of the fusion-fission hybrid is similar to comparably sized LWR reactors. Under blanket melting conditions, the fission products are expected to exhibit mobility and transport characteristics similar to LWR designs.
- The hybrid operating on the uranium cycle produces an actinide Biological Hazard Potential (BHP) on the same order of magnitude as the LMFBR and GCFR. On the thorium cycle however, the BHP is reduced by two orders of magnitude below the two fast reactors and nearly a full order of magnitude below thermal reactors.
- The pursuit of the low-consequence fission-suppressed hybrid blanket concept could conceivably reduce the actinide BHP an additional one or two orders of magnitude while maintaining a high fissile production to thermal power production ratio and therefore appears to be a worthwhile venture.
- Activation product BHP's approximate those of pure fusion and do not significantly contribute ($\approx 1\%$) to the hazard potential of the mainline fast fission hybrid.
- Tritium and gaseous fission products in the blanket are the most mobile radioactivity sources and, in most cases, there are several barriers that must be breached before radioactivity can be released to the environment. However, if the fusion vacuum boundary or any of the tritium injection system piping is breached in the reactor chamber, the only barrier to release of radioactivity

is the secondary containment. Therefore, a probabilistic risk assessment of various tritium containment concepts would be a useful task.

- The tritium inventory present in the hybrid design is not as biologically significant as the majority of the blanket fission products, actinides or activation products, however, it is highly volatile, mobile and present in large quantities within the reactor systems and support equipment. It is recommended that a task be undertaken to determine the rate of diffusion of tritium from various components of the fusion reactor. This information is needed to determine the necessary rate of isolation valve actuation to preclude tritium release from parts of the system away from the failure point. The information is also needed to evaluate detritiation system performance requirements.

This recommendation would also apply to pure fusion safety studies but is included in the hybrid area because it is felt that the tritium system and tritium release mechanisms will dominate the low consequence, high probability portion of the risk envelope for the hybrid facility. The relative risk potential of the tritium systems in a hybrid reactor should be assessed.

- In considering ways in which radiation can be released to the atmosphere, it was pointed out that the unique feature of the hybrid is the potential for coupled fusion-fission accident events. For example, if a failure in the fission blanket system can lead to a failure in the fusion system, then the consequence may be more serious than a separate failure in either system. This area requires further study and evaluation of all possible coupling accidents.
- Analyses should be undertaken to evaluate the effect on structures due to what was termed neutron attenuation anomalies in Section 5.4. A failure of shielding in the fusion reactor could cause unexpected neutron heating of the vacuum vessel or other components and result

in a local hot spot. A failure of shielding in the fission blanket could lead to excess power production in the blanket and possible thermal failure of blanket fuel elements.

- A preliminary bounding study examined the aspects of hybrid blanket heating with subsequent radionuclide release to the containment building atmosphere. Conservative selection of blanket activity release, accident scenario conditions and meteorological dispersion parameters ensure a bounding determination of the hybrid reactor's consequence potential. As a result of this study, the following conclusions are made:

- (1) The tritium dose is negligible by comparison to fission and activation product inventory contributions.
- (2) Activation product radionuclides contribute approximately 25% of the total lung inhalation dose.
- (3) Fission product radionuclides contribute all the thyroid dose commitment.
- (4) The actinide inventory for the uranium blanket dominates the bone dose category. (Plutonium isotopes contribute 95.7% of the reported dose). Additionally, the bone dose of 290 rem exceeds the 10CFR100 limit by approximately a factor of 2.
- (5) From the standpoint of radiological considerations, specifically bone dose, the thorium hybrid blanket is more attractive than the uranium-blanket counterpart.
- (6) Both blankets were evaluated in a secondary containment structure leaking to the environment at a nominal leak representative of a modern LWR lined containment. Since the resultant consequences for either blanket design are close to 10CFR100 limits, it is doubtful if an unlined or more "leaky" containment would be tolerated in the hybrid

programs. It is possible that perhaps a double containment option may be necessary if the assumed source term of 1% of the accumulated fuel activities is indeed applicable. In fact, with proper design guidance, mechanisms for this 1% release may not be identifiable for the hybrid reactor.

These observations from the preliminary safety survey completed during FY79 allow an initial assessment of the significant safety aspects of the fusion-fission hybrid reactor concept. They have formed a basis for the recommendations of the hybrid safety program plan. Investigation of hybrid design alternatives to reduce the hazard potential, dose consequences and risk uncertainties that were identified here comprise the major portion of the initial phase of the proposed hybrid safety program.

REFERENCE

- 1.1 D. L. Jassby, editor, "Workshop Summaries," Proceedings of the Third US/USSR Symposium on Fusion-Fission Reactors, Princeton, N. J., January 1979.

2. DESCRIPTION OF HYBRID SYSTEMS

A fusion-fission hybrid reactor is simply a fusion reactor with a blanket of fertile and/or fissile material around it to utilize the fusion neutrons. The neutrons may cause fission, thus enhancing the energy production of the fusion reactor or may be captured in fertile materials to produce fissile fuel. In most potential applications, a combination of energy and fuel production is obtained.

The fusion-fission concept was first proposed in 1954 as a possible means of producing plutonium (2.1). Next it generally was looked upon as a means of energy enhancement to allow low performance fusion drivers to achieve a positive power balance. Most recently, hybrid fusion is being looked to as a possible fuel breeder for fission burner reactors with power production as an important (and perhaps necessary) by-product. An excellent summary of earlier work may be found in Ref. 2.2 while more recent studies are reported in Refs. 2.3 through 2.6.

The hybrid concept is of interest today as a potential copious source of fissile fuel. The additional energy produced in the hybrid blanket can help the fusion driver achieve a positive energy balance. The energy and the fuel produced can help fusion become economically attractive. The energy and economic enhancement may allow the performance requirements imposed upon the fusion driver to be relaxed somewhat although it appears that a good hybrid reactor will require a good fusion driver. Relaxed fusion performance requirements and enhanced economics could allow earlier application of fusion power than would be possible via electrical power production alone.

The fusion-fission concept also poses potential disadvantages to fusion. The design considerations of the reactor blanket are complicated by inclusion of fission. Safety considerations may be similar to those of fission reactors.

The political implications of fusion power being perceived by the public as simply a means to produce fissile materials could threaten the entire fusion program. Although the technical potential of the fusion-fission concept appears good, its role in the U.S. fusion program appears to be still undecided.

A major consideration in the perception of the fusion-fission hybrid concept is safety. The addition of a hybrid blanket to a fusion driver can introduce the same environment and safety concerns that are raised with fission reactors. A hybrid, however, has design differences that could result in significant safety differences between fission, fusion and hybrid systems. The complicated geometry of many fusion systems and presence of vacuum chambers and magnetic coils could result in additional potential accident pathways. The possibility for assured blanket subcriticality could allow any reactivity accidents to be completely avoided. The great degree of flexibility for blanket design choices can allow a wide variety of designs with various safety characteristics to be considered. The establishment of a hybrid reactor safety program to guide the safety development of the hybrid concept at the present pre-conceptual development stage is highly desirable in that it can allow the hybrid concept to be optimized for safety.

2.1 REACTOR DESCRIPTION

The mechanical features of a hybrid reactor are virtually identical to those of a fusion reactor. The reacting fusion plasma is surrounded by the vacuum chamber first wall beyond which a blanket region captures the fusion neutrons. Beyond the blanket lies a shield to protect reactor components from radiation damage and neutron activation. The first wall, shield, power conversion system and balance of plant can be identical to those of a fusion reactor. The blanket, however, is different. In a fusion reactor the blanket must convert the neutron energy to heat and breed tritium to sustain the fusion reaction. In a hybrid reactor the blanket must also produce fission energy and breed fissile fuel.

2.1.1 Fusion Drivers

Hybrid reactors based on all types of fusion drivers have been proposed. Their different operating characteristics can affect the safety concerns of the reactor.

Tokamaks. The tokamak is the leading fusion reactor concept because of its capability for high plasma power amplification (Q_p). As presently understood the tokamak will operate in a long-pulse mode with tens of seconds between pulses, allowing significant temperature fluctuation during the operating cycle with the potential for enhanced structural problems. The toroidal geometry of the tokamak complicates structural design and may result in blanket geometries that could be difficult to cool under accident conditions. The good plasma performance of a tokamak can allow use of low multiplication, low power density blankets that may have significant safety advantage.

Mirrors. The standard mirror reactor is characterized by low plasma power amplification but can operate in a steady state mode. The low Q_p capability implies the need for a significant fission rate in the blanket to provide energy multiplication. This in turn implies higher power densities, higher temperature gradients, a higher fuel burnup and higher fission product inventories, all of which tend to exacerbate safety concerns. Enhanced- Q mirror concepts like the tandem mirror, although unproven, may allow use of lower power blankets which could improve safety.

Inertial fusion. Inertially confined fusion would operate with very brief, intense pulses of power. By keeping the pulse repetition rate faster than the thermal time constant of the fuel (> 1 to 10 Hz), temperature oscillations may be minimized. The absence of magnetic fields makes possible the use of materials that may be more difficult to use with magnetically-confined fusion, and may eliminate magnetic-related accident initiation events.

2.2 DESIGN STATUS

2.2.1 Modes of Hybrid Operation

L. Lidsky proposed classifying fusion-fission reactors as "symbiotic" if they produced fuel, "hybrid" if they produced energy and "augean" if they used fusion neutrons to burn fission reactor waste products (2.7). Recognizing the continuum of modes between a fuel producer and an energy producer, this report will use the definitions "fuel producing hybrid" for reactors whose main product is fuel, "energy producing hybrid" if the main product is energy and "fuel and energy hybrid" if both products are important. Recent concern about nuclear proliferation and diversion has prompted consideration of the "refresh cycle" concept in which fuel produced in the hybrid would be used directly in a fission burner reactor without reprocessing.

2.2.2 Augean Systems

Fusion can provide a plentiful source of 14 MeV neutrons which could be used to fission and transmute long-lived fission reactor waste product actinides and fission products into stable or short-lived materials, thus helping to alleviate waste disposal concerns. A design study for a tokamak actinide waste burner was done by Westinghouse in 1976 for the Electric Power Research Institute (2.8) which showed that a significant exposure to fusion neutron flux was required to appreciably reduce the waste disposal concerns. This raised significant structural materials damage concerns. Basically, exposure sufficient to significantly affect the actinide inventory also significantly affected the reactor fuel and structure materials. To attempt to solve these materials problems, General Atomic in 1977, also under EPRI sponsorship, proposed use of the liner fusion concept with a rotating molten-salt fluid blanket that would operate at average wall loads of about 100 MW/m^2 (2.9). With no internal structure, such a blanket would be immune to structural materials damage concerns. The safety implications of the very large radioactive inventories present in these reactors were not explored in any depth but the very large hazard potential associated with the fission product or

actinide inventories of many fission reactors that would be present in an augean system and the high power densities present in these blankets are sure to raise formidable safety problems.

The augean fusion-fission reactor studies indicate that a significant impact on the fission reactor waste disposal problem could be made, but that there are appreciable mechanical, thermal, safety, and materials problems associated with augean systems. Conventional waste disposal techniques appear to be technically quite straightforward and would be needed for disposal of augean reactor system residues. As a result, it appears that augean systems are really not worth the effort.

2.2.3 Energy Producing Hybrids

The energy producing hybrid would produce and consume fissile fuel in situ, producing energy as its only external product. A hybrid reactor design study done at Princeton Plasma Physics Laboratory explored this concept (2.10). Since the burnup goal of the energy producing hybrid is 100%, very high fluences and burnup levels are encountered. The fuel and structure will have to be replaced periodically. The energy producing hybrid provides a challenging design environment. A high blanket multiplication factor gives high power density, high afterheat levels and a significant radioactive inventory with concomitant safety concerns. It appears that the bred fuel would be better used in an external fission burner reactor where additional fertile conversion can improve fuel utilization.

2.2.4 Fuel and Energy Producing Hybrids

In the fuel and energy producing hybrid, fissile fuel is the primary product although significant amounts of energy may be produced by fast fission of the fertile material. The best overall blanket performance in terms of fuel and energy produced can be obtained from this sort of fast fission hybrid blanket (2.11). Both Westinghouse (2.12) and the Lawrence Livermore Laboratory/General Atomic team (2.13) have proposed plutonium-producing hybrids based on fast spectrum uranium blankets. More recently

Westinghouse has proposed a water-cooled thorium oxide blanket for a Demonstration Tokamak Hybrid Reactor (2.14). Although the DTHR itself is not intended to produce electricity, a significant amount of fission occurs in the blanket and upgrade versions of this design would produce electricity. Recent work on the mirror hybrid concept has also focused on thorium fuel. Fast fission blanket designs for the Tandem Mirror Hybrid Reactor (2.15) have been pursued by both General Atomic Company (gas-cooling) and General Electric Company (water-cooling).

Because of its excellent fuel and energy production characteristics, the fast fission fuel and energy producing hybrid blanket appears to be the "mainline" blanket concept. The design environment of this blanket is challenging due to the high temperatures, power densities and flux levels that are present, although this reactor appears to be an easier proposition than either the augean or energy producing hybrids. As will be discussed in Section 5.1, the fuel and energy producing hybrid appears to have radioactive hazard inventories similar to those of fission reactors and it is expected to have similar overall safety characteristics.

2.2.5 Fuel Producing Hybrids

A fuel producing hybrid would attempt to minimize the energy production in the blanket by suppressing fission. Neutron multiplication through (n,2n) reactions might be used to improve breeding performance. The intent in suppressing fission is to simplify blanket design considerations by operating at low power density with low afterheat. Although the fission-suppressed blanket has been proposed by several authors (2.7, 2.16) a full design study of such a system does not yet appear to have been done. Preliminary calculations done at General Atomic with graphite-base thorium blankets and at LLL with molten thorium salt blankets indicate that ^{233}U production rates of 0.2 to 0.8 atoms per fusion neutron can be achieved with unity tritium production (2.15). Work is presently being done at LLL with General Electric Company to complete an initial preliminary conceptual design of a Tandem Mirror Hybrid Reactor with a thorium molten salt blanket.

Although the fuel production capability of the fission-suppressed blankets appears modest compared to fast fission blankets, the much lower energy production allows the fuel production per unit of hybrid reactor power to be quite high. This allows a large number of fission burner reactors to be supported by one hybrid reactor. The relative advantages of high performance, high support ratio, design simplicity and potential safety improvement are still being argued. In the final analysis, the fission suppressed hybrid may prove to be more desirable than the mainline fuel and energy producing hybrid.

2.2.6 Refresh Cycle Hybrids

The refresh cycle concept is a unique application of fusion power to the production of fissile fuel for burner reactors under the unusual stipulation that reprocessing of the bred fuel not be allowed due to concern about nuclear proliferation and diversion. Fertile material would be irradiated in the blanket of a fusion reactor and then transferred, without reprocessing, to the thermal burner reactor. After discharge from the burner, the fuel could be returned to the hybrid reactor to have its fissile content "refreshed."

The refresh cycle has been investigated at General Atomic for ^{233}U fuel based on HTGR technology (2.17), at the University of Wisconsin for ^{233}U fuel based on LWR technology (2.18), and at Westinghouse for ^{239}Pu fuel based on LWR technology (2.19, 2.20). The safety aspects of the refresh cycle hybrid appear to be about the same as that for the fast fission hybrid in that significant radioactive inventories will be present. The concept appears feasible but requires further study. The fuel consumption in a thorium cycle converter reactor without reprocessing can be three times that of the same reactor if reprocessing is allowed. The rationale for the no-reprocessing edict needs to be fully assessed. The design and performance of refresh cycle systems must be pursued in more depth. Nevertheless, if proliferation and diversion concerns rule out reprocessing, the refresh cycle fusion hybrid could still provide fuel for thermal burner reactors.

2.2.7 Mainline Assumption

The fast spectrum fuel and energy producing hybrid blanket concept will be used as the basis for this discussion, as it appears at present to be the mainline hybrid concept. The understanding of hybrid reactor systems, however, is advancing and serious assessment of the relative merits of the many blanket, driver and operating mode possibilities is just beginning. A strong contender for the "optimum" hybrid system may be a fission-suppressed type of fuel producer. If this proves to be the case, the design requirements of hybrid systems should be somewhat relaxed, as discussed above. An incentive toward the fusion-suppressed blanket concept is the potential for safety advantages. This potential needs further study to assess and quantify.

2.2.7.1 Blanket Performance. Interaction of the 14 MeV D-T fusion neutrons with the fertile materials in the fast fission blanket of a hybrid reactor can result in significant neutron and energy multiplication. Both uranium and thorium exhibit significant (n,2n), (n,3n) and (n,fission) reactions with 14 MeV neutrons. The average performance characteristics of typical fast spectrum uranium and thorium blankets are shown on Table 2.1 (2.13, 2.15). Both blankets can produce significant amounts of fissile fuel. If this fuel is assumed to be burned in a thermal spectrum fission reactor, a large number of burner reactors could be supported by each hybrid reactor. The lower breeding performance of the thorium blanket is offset by the higher value of the bred ^{233}U as a fuel for thermal burner reactors (2.21). Use of more efficient thermal converter reactors, such as the HTGR, can further enhance the hybrid reactor support ratio, as shown.

2.2.7.2 Design Environment. In addition to bred fissile fuel the hybrid blanket can also produce significant energy multiplication, by fission, of the fusion neutron energy. This can produce very high power densities in the blanket fuel material. The fuel of the Standard Mirror Hybrid Reactor, for example, experienced a peak power density of 500 W/cm^3 at 2 MW/m^2 wall load. Since the hybrid blanket can experience a significant fission power

density, it can build up a fission product inventory with its associated afterheat and radiological hazard potential. The initial steps in the analysis of the safety aspects of the assumed mainline hybrid concept and the initial steps to identify safety concerns and point the direction for design changes to avoid these concerns is the purpose of this Hybrid Safety Study.

TABLE 2.1
TYPICAL FAST FISSION HYBRID BLANKET PERFORMANCE CHARACTERISTICS

Characteristics	Uranium Blanket (2.13)	Thorium Blanket (2.15)
Fuel Production (atoms/fusion neutron)	1.5	0.75
Energy Multiplication (M)	10.4	3.0
Fuel Production (kg/MW fusion-yr)	6.5	3.2
Fuel Production (kg/MWth-yr)	0.76	1.25
Support Ratio* - LWR	4.0	9.6
(P _e -burner/P _e -hybrid) - HTGR	---	20.7

* Assumed fuel consumption (kg/GW_e-yr): LWR-Pu, 533 kg;
LWR - ²³³U, 360 kg; HTGR - ²³³U, 168 kg

2.3 HYBRID SAFETY DESIGN STATUS

This section reviews safety-related design features as presently incorporated and described in the two major published hybrid designs, the LLL/GA Standard Mirror Hybrid Reactor (MHR) (2.13), and the Westinghouse TCT Hybrid Reactor (2.12). Design features incorporated in these designs include the following: plant control and plant protection systems to insure safe reactor shutdown during both normal operation and emergency situations, normal and emergency cooling for the fissioning blanket, containment atmosphere cleanup systems, superconducting magnet protection, and a secondary containment system.

The above features are described, followed by a discussion of the safety potential of fission-suppressed, low consequence hybrid blanket designs. Since the safety work done for the Westinghouse reactor consisted mainly of the identification of safety concerns, most of the engineering detail presented herein was abstracted from the MHR design. Due to the importance of the potential for hybrids to be designed and operated to totally avoid criticality concerns, this topic is discussed first.

2.3.1 Subcriticality of Hybrid Reactors

An inherent feature of hybrid breeder reactor fissioning blankets is the potential for maintenance of a substantial degree of subcriticality. In essence, the blanket is a breeding sub-critical assembly. Conceptually, there are three ways in which multiplication can increase. The first is for fissile production to remain unchecked until the blanket either equilibrates or achieves criticality. Preliminary calculations for a uranium blanket indicate that the plutonium concentration equilibrates before criticality is reached (2.22). The second is for moderating material to enter the blanket. Neutrons, moderated by the inserted material could, with a sufficiently large fuel rod pitch, be thermalized by the moderator and could avoid the resonance absorption energy range. The blanket neutron multiplication could thereby be increased. For the MHR configuration, the small volume of moderator (water) allowed by the very tight fuel rod spacing would not allow significant neutron moderation. The neutrons would remain in the resonance region, would not thermalize, and would result in lower multiplication.

Lastly, the fuel could geometrically be reconfigured into a critical arrangement. This could potentially occur from the following causes: fuel melting as a result of a loss of coolant accident or inadvertent neutral beam penetration into the blanket, and major changes in fuel geometry from fuel motion caused by earthquakes or magnet system malfunctions. Magnet system malfunctions could potentially lead to large unbalanced forces on the blanket modules. Of these malfunctions, loss of coil current can be

survived without catastrophic damage by the magnet supports absorbing the forces and subsequent stresses and distortions. For partial or total magnet quench, a reliable quench detection and protection system is envisioned to protect the coils from damage. This is described in the next section. It is expected that the forces generated by even unexpected magnet failures can be contained, without mechanical motion that could endanger the blanket structure, coolant piping or fuel configuration, by proper design of the coil support structure. The effect of earthquakes and seismically induced blanket vibratory motion depends on the soil stiffness and damping factors of construction. Design against these concerns is standard in the fission industry. Fuel melt from the unattenuated neutral beams requires penetration of the liner and vacuum vessel. An analysis by Westinghouse indicates that this event is not likely. Finally, protection against a loss-of-coolant accident is discussed in the next section.

In conclusion, the protection systems incorporated to prevent the above accidents from occurring and possibly providing the mechanism for reactivity insertion, coupled with the low burnup and low plutonium concentration of the blanket show criticality to be extremely difficult to achieve. Furthermore, due to the low k_{eff} of the blanket, even a large reactivity insertion should not result in any significant power increase, resulting in a low probability, low consequence and therefore, low risk event. This is a potentially significant advantage of hybrid reactors.

2.3.2 Safety-related Design Features

The design features listed in the introduction to Section 2.3 are now discussed. The first is the plant control system. The MHR plant control system ensures the safety of the plant during normal operations, and in the event of an abnormal or accident condition, provide for orderly shutdown. It consists of two distinct sub-systems: the Plant Control System (PCS), which regulates the plant in all normal modes of operation, including loop or reactor trip or electrical load rejection, and the Plant Protection

System (PPS), which initiates action to protect the fission product barriers and limits a radioactive release if a breach of these barriers has occurred.

The portion of the PCS with safety concerns is the residual-heat-removal control system. Its functional requirement is to automatically provide adequate blanket cooling during the transition from normal operation to long-term decay-heat removal operation in all shutdown situations, including the Design Basis Accident (DBA). The following actions are initiated for reactor shutdown subsequent to a reactor trip signal:

1. Neutral beam injector power is removed. (For an ignited system, fueling and plasma current drive would be stopped.)
2. Startup of the auxiliary steam supply system is initiated.
3. Main turbines are tripped.
4. Resuperheater bypass circuits are activated simultaneous with turbine trip and are controlled by signals from the PCS.
5. Circulator turbine large control valve is closed as the neutron flux decreases.
6. Circulator turbine small control valve is controlled by signals from the PCS.
7. Shutdown boiler feedpumps are activated.
8. Auxiliary cooling system is activated as backup to main.
9. Emergency diesel generator sequence is initiated to provide backup.

Once the power has been reduced to a sufficiently low level, orderly transition to the decay-heat-removal control system commences. This control system is required to provide adequate cooling for indefinite periods.

The PPS initiates proper action to prevent blanket radioactivity release. This is accomplished by monitoring critical plant parameters, and should any of these exceed safety limits, actuating reactor trip and if necessary, the plant accident mitigation systems. The main tripping parameters are the power level and power-to-coolant-flow ratio. Other tripping parameters include high coolant moisture, high delayed-neutron activity, high or low coolant pressure, etc. Concurrent signals of loop trouble and low reactor coolant pressure actuate fast transfer to emergency cooling with the auxiliary loop. In addition, high containment pressure or high containment radioactivity actuate automatic containment isolation and atmosphere cleanup.

Assured shutdown cooling using forced circulation in all normal and emergency situations is a fundamental safety requirement. The parts of both cooling loop systems necessary for emergency cooling of the MHR are designed to maintain their function during transients and postulated accidents, including earthquakes, loss of offsite power and single equipment failures. In the event of failure of any main loop, operation at reduced power could be continued, if desired, due to manifolding of all main loops. The auxiliary loop circuitry is arranged so that failure of one circulator or heat exchanger, the remaining units could still provide adequate cooling. In the event of a depressurization accident, the main cooling loops would continue to provide shutdown cooling with the auxiliary system providing an independent and diverse backup. High pressure accumulators may be needed to provide immediate supplementary cooling until auxiliary circulators, emergency power supplies, etc., could be brought into operation.

To minimize tritium exposure to the general public during normal operation, the tritium concentration inside the reactor hall is kept low. This is accomplished by 1) maintaining a space between the building shell and a hermetically sealed liner below a prescribed tritium level, 2) providing the entire wall surface area with a 2 mm stainless steel permeation barrier, and 3) employing a tritium removal system to process the reactor

hall air and maintain tritium levels below a prescribed level on a steady-state basis. Tritium leakage into the reactor hall is minimized by the use of double wall ducting wherever tritium is expected, separately monitored and connected directly to the reactor hall air processor. The reactor hall air processor is itself contained in a vault and separately purged and processed. Air locks connecting the reactor hall to the outside are also provided to minimize tritium out-leakage.

In the event of a tritium accident, the processor will be capable of handling the maximum credible tritium spill. However, a trade-off exists between the desired cleanup time and the catalyst bed costs. Escape of workers during a serious spill is provided by breathing booths and escape ducts to the outside.

Superconducting magnets store an extremely large amount of energy. Catastrophic failure of the magnets may potentially induce blanket rupture, prompting the release of radiological hazards although this appears to be highly unlikely. For this reason, magnet failure protection is a primary design goal. Protection against local thermal events and local quenches is an inherent feature in cryostabilized magnet designs. The magnet protection system proposed for the Westinghouse hybrid consists of emergency cooling by liquid helium from an accumulator. Provisions have been made to dump stored magnetic energy through an external resistor and heat exchanger if necessary. The detection of quenching of any conductor within a magnet would actuate quick-acting valves, releasing high pressure, sub-cooled helium into the magnet. In case of a partial quench, a two-stage system of recovery is proposed in which first an attempt is made to recover via increased coolant flow, followed by removal of the stored energy. The main purpose in magnet safety systems is protection of the magnets. Despite the large amount of stored magnetic energy, magnet safety studies indicate that major structural damage to the reactor, caused by the magnet, is unlikely.

The secondary containment building is a standard design of fission reactors and therefore needs no further discussion. The MHR further

incorporates a prestressed concrete reactor vessel (PCRV) to provide the safety functions of main coil force restraint, pressure containment, positive constraint of helium coolant ducts, and biological shielding. Gross failure of the basic PCRV structure is not considered possible.

This completes the discussion of present hybrid reactor safety design. As evident from the above, detail is admittedly sketchy, though this is to be expected for the level of development of the hybrid. The important point to note however, is that preliminary consideration is being given to safety issues in hybrid designs. The safety design features considered to date have been strongly oriented toward conventional fission reactor practice with some additional fusion reactor consideration for tritium and magnets. No unique hybrid safety design features have yet been identified. Of greater importance is the necessity to incorporate safety as an inherent quality in the design of this evolving concept. An additional consideration is the minimization of consequence in the event of a serious event. One possibility with this inherent feature is the low-consequence blanket design discussed in the next section.

2.3.3 Low-consequence Hybrid Blanket Concept

The idea behind the low-consequence blanket is to minimize the risk associated with a hybrid's fissioning blanket by lowering the consequence of an accidental event. The vehicle used to arrive at the lower consequence is the suppression of the actinides and fission products with the highest biological hazard contribution. This entails the use of thorium as the fertile material and the suppression of (n,f), (n,2n) and (n,3n) reactions by softening the 14 MeV fusion neutron spectrum, for example by placing the thorium behind the tritium breeding zone. This minimizes the neutron population above the energy threshold of the fission and multiple neutron emission reactions of thorium and reduces the main production pathway for Th-228, U-232, and Pa-231, the primary contributors to actinide BHP.

Two general concepts have been identified to minimize fission in a hybrid blanket. The first is to dilute the fertile material with moderators

such as water, graphite or molten salt constituents so that the spectrum is softened and employing frequent or continuous reprocessing of the fuel mixture to remove bred fissile material. An example of this is the molten salt hybrid blanket proposed by LLL (2.23). This concept uses the molten salt compound $\text{LiF} \cdot \text{BeF}_2 \cdot \text{ThF}_4$ with additional beryllium for neutron multiplication. This material provides a high tritium breeding ratio but employs beryllium as a neutron multiplier and is thus subject to beryllium resource limitations. The other concept employs metallic thorium or thorium compounds behind the tritium breeding zone, softening the neutron spectrum, and also uses lithium to suppress the thermal neutron spectrum, preventing fission of the bred fuel. Preliminary calculations have been performed for this configuration and show a reduction in multiple neutron emission and fertile fast fission reactions by 1-2 orders of magnitude compared to fast fission blankets while maintaining a high fissile production to thermal power production ratio (2.24). Since this is the primary purpose of deploying breeder reactors in general, and appears to offer the potential for significant safety advantages, the low-consequence blanket option should be vigorously pursued.

2.4 SYSTEMS FOR ACCIDENT MITIGATION

In addition to the inherent and designed safety features presently included in hybrid designs as described in the preceding section, other accident mitigation systems to restrain the advance of an accident and/or diminish its consequences can be conceived. A listing, though by no means exhaustive, of such systems is provided in Table 2.2. A brief description of those accident mitigation systems not described in Section 2.3 follows.

The most visible of the accident mitigation systems is the secondary containment building. This might be of the containment/confinement type, as in GCFR. The confinement building would serve as an additional barrier external to the containment and providing a time-delay mechanism in the event of containment building release. The secondary containment would serve as the massive structural member familiar to fission reactors. To diminish the

TABLE 2.2
SYSTEMS FOR ACCIDENT MITIGATION

Secondary Containment/Confinement
Compartmentalization
Tritium/Fission Product Detection/Cleanup
Sub-Criticality
Post-Accident Fuel Containment
Lithium Containment
Inclusion of Blankets Within Vacuum Chamber
Double-Walled Piping
Plant Protection and Control Systems
Redundant and Diverse Cooling
Magnetic Energy Dissipation System
Plasma Disruption Protection Armor
<u>Low Consequence (Fission Suppressed) Blanket Designs</u>

the possibility of large releases to the containment/confinement, compartmentalization could be employed under the premise that smaller volumes are easier to control and to provide an additional barrier, especially for the tritium systems. In the event of a spill, a detection/cleanup system for tritium as well as fission products would have to be provided. These might be located in each compartment as well as in the containment, with separate circuitry, in order to provide a high level of redundancy.

An inherent feature of hybrid reactors, as discussed above, is the potential for absolute subcriticality. In the improbable event of a fuel melt, a system for post-accident fuel containment (a "blanket catcher") may be incorporated to insure containment and, if the fissile content is high, subcriticality of the molten mass. Other liquids capable of accident initiation or propagation, such as lithium, might be provided with additional containment boundaries. The entire blanket might be included within the vacuum chamber as an additional barrier to the release of biological hazards.

Hybrid reactors are a new technology with attendant vestiges of uncertainty and the unknown. Incorporation of the above systems, and others, will make hybrids safe, but the decision to include them or not will best be answered by the cost-benefit analyses that will be performed during the detailed design stages. It is important that safety design features for accident mitigation be considered and evaluated as an integral part of the growth of the concept in order that socio-political implications not be unanswered when the hybrid is first unveiled in the public eye.

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3. REVIEW OF PREVIOUS WORK ON HYBRID SAFETY

This section will briefly review the work to date in the area of fusion-fission hybrid reactor safety. The review will be limited to magnetic plasma confinement concepts, inertial confinement fusion-fission hybrid design being beyond the scope of this Hybrid Reactor Safety Program Plan.

As described in Section 2, the fusion-fission hybrid reactor is comprised of a fusion device supplying a neutron rich spectrum to the blanket surrounding the fusion driver. Safety studies associated with conceptual fusion reactor designs are widely reported in the literature (3.1-3.22). These studies are, in general, quite applicable to the fusion driver of the fusion-fission hybrid, and will not be reviewed at this time; however, the fissioning blanket surrounding the fusion driver is subject to unique safety concerns. Some of these hybrid blanket related safety concerns have been addressed in preliminary safety examination studies (3.23-3.31), some of which will be discussed at this time.

Two of the more mature hybrid reactor designs are the Lawrence Livermore Laboratory/General Atomic Co. design (LLL/GA) (3.23) and the Westinghouse Tokamak breeder design (3.25). Both designs are optimized for fissile fuel production and use fast fission of the fertile material to enhance neutron production and to produce large amounts of energy for a low plasma amplification (Q_p) fusion driver.

3.1 THE WESTINGHOUSE TOKAMAK BREEDER DESIGN (3.25)

The Westinghouse hybrid design study (3.25) incorporates a scoping exercise which identified likely candidates for design basis accident consideration. The principal areas identified were loss-of-coolant accident and blanket criticality concerns.

Additionally, potential malfunctions of the superconducting magnet systems were identified as having sufficient potential energy to perhaps disrupt the structural integrity of the magnets themselves and the adjacent blanket system.

3.1.1 Loss of Coolant Accidents

In loss-of-coolant accidents, the Westinghouse hybrid study identified the requirement for an established emergency cooling system, as the predicted time to blanket fuel element melting initiation is estimated to be 100 seconds with no emergency cooling. This rather rapid heatup is dictated by the high power density and limited thermal capacity of the blanket coupled with the fact that the hybrid breeder fission product inventory (and its attendant decay heat source) is on the same order as that of a 1000 MW(e) LWR plant.

3.1.2 Blanket Criticality Concerns

The blanket of the Westinghouse design is substantially subcritical under normal operating conditions, however, there may be conditions under which the blanket/fuel geometry may change sufficiently to provide a supercritical condition. Only qualitative discussions of criticality concerns were made, detailed blanket neutronic calculations of criticality conditions were beyond the scope of the Westinghouse study. Kastenbergh, et al., (3.31) have considered in a quantitative fashion the aspects of hybrid reactor criticality as summarized in Section 3.3.

3.1.3 Neutral Beam Failures

The Westinghouse study concluded, that for the current Westinghouse Hybrid design, unattenuated neutral beam injection may be of sufficient energy and duration to strike and melt through the liner and partially melt the vacuum vessel wall. However, the study concludes that the possibility of neutral beams reaching the fuel pins is quite small.

3.2 LLL/GA STANDARD MIRROR HYBRID REACTOR DESIGN (3.23)

The LLL/GA Standard Mirror Hybrid Design Study (3.23) identified two aspects of blanket safety concern during accident conditions, 1) loss of coolant flow related blanket heatup and 2) rapid depressurization effects on the primary coolant loop structures.

3.2.1 Blanket Safety Evaluation

The LLL/GA study concludes from preliminary adiabatic heatup estimates, that in the event of loss of blanket cooling, the time available before fuel reaches its melting temperature is 24 seconds (assuming the reactor is shut down). This time is reduced to 1.5 seconds if the loss of cooling occurs at full power. The LLL/GA safety assessment concludes that the blanket cooling requirements will impose stringent demands on the response time and reliability characteristics of the auxiliary cooling system.

3.2.2 Plant - Safety Concerns and Issues

Potential accidents were examined and from these, the design basis accident chosen was a postulated failure of the helium ducting, causing rapid depressurization of the blanket coolant into the containment building.

Forces during rapid depressurization of the primary coolant loop have been considered in the LLL/GA hybrid design and are limited by the installation of flow limiters (Venturis) on the exit manifold of each blanket module. Damage to the fuel support grid is expected in the event of a rapid depressurization, however a coolable geometry is expected to be maintained.

Additionally, the following subjects were treated in the safety analysis in a qualitative fashion; reactivity insertion accidents, local flow blockage accidents secondary coolant leakage, blanket coolant leakage and PCRV failure.

3.2.3 Safety and Environmental Effects

The major potential hazards associated with the LLL/GA hybrid design were identified in the study to be the fission products, actinide elements, tritium and induced activity in the blanket structural material. The major threat to public safety appears to be through the release of these materials to the environment, subsequent to blanket fuel melting. Due to the low burn-up and low fissile concentration anticipated in the blanket, criticality was estimated to be difficult to achieve. Coupled fusion/fission events may have potential effects on the safety integrity of the blanket, e.g., gross magnet failure.

Other potential blanket events of safety concern identified and briefly discussed in the LLL/GA study include overpower transients, undercooling transients, fuel handling accidents and steam generator accidents.

The LLL/GA safety evaluation concludes that adequate description of public risk associated with the fusion-fission hybrid concept must, for completeness, examine the total fuel cycle. A proper perspective of the hybrid breeder reactor risk individually as well as the cumulative risk of the entire LWR plutonium fuel cycle should be determined.

3.3 ON THE SAFETY OF CONCEPTUAL FUSION-FISSION HYBRID REACTORS - W. E. Kastenberg, et al. (3.31)

The four major potential hybrid reactor hazards identified by Kastenberg, et al. (3.31) were tritium, activation products, actinide elements and fission products. Event trees were constructed for those events which might release the above hazardous material to the environment. Major sequences of safety concern unique to the fusion-fission hybrid reactor were identified as follows:

1. Blanket loss-of-flow accident.
2. Blanket loss-of-coolant accident.
3. Steam-ingress accident.
4. Plasma density-temperature accident.

The above accidents are discussed in some detail. Conclusions reached indicate that in particular, loss-of-coolant and criticality appear to be the major generic safety considerations unique to fission blankets.

3.3.1 Loss-of-Coolant Accident

Aspects of the blanket LOCA and of a blanket steam-ingress accident were examined in detail. In summary, the work demonstrates that significant LOCA or steam-ingress damage to the blanket, fuel-element containment and structural components of the reactor can occur in the range of 1 to 10 seconds. This time interval is characteristic of the reactor shutdown time and therefore it may be difficult to trip the reactor before significant damage has occurred to reactor components.

The authors conclude that highly reliable and redundant decay-heat removal must be provided to remove the shutdown reactor's first-wall after-heat and blanket fission product decay heat.

3.3.2 Hybrid Blanket Criticality Concerns

For the LLL/GA hybrid reactor design, the study concludes that criticality would be difficult to achieve. Blanket meltdown, blanket compaction and steam ingress, under normal blanket residence times (low to intermediate U-238 burnup) would not produce a critical configuration. Critical configurations may be produced by steam/water ingress accompanied by blanket expansion, however, a source of the water required (3 times the steam generator inventory) is not present in the design examined.

3.3.3 Fission Product and Actinide Blanket Inventory Estimates

Hybrid reactor fission product and actinide inventory estimates were made incorporating consideration of $(n,2n)$ and $(n,3n)$ reactions and the consideration of high energy fission product yield distributions at 14.1 MeV. Hybrid inventories for a 1 GW(t) blanket after 3 years of operation with and without consideration of $(n,2n)$ reactions were compared to an equivalent

thermal power LWR. It was concluded that predicted fission product inventories with and without consideration of the (n,2n) reaction do not differ significantly from the LWR fission-product inventory for the same energy production level. However, Pu-239 inventories were found to be approximately 12 times larger for the hybrid blanket than the LWR inventory.

3.3.4 Tritium Hazards

The hazard presented by continuous daily leakage of low level tritium discharges and estimates of the hazard due to short term or near instantaneous accident-released tritium from hybrid reactor systems were modeled through the use of TREM computer model (3.3). For accident considerations, the dose commitment to the surrounding population within 80 km of the hybrid facility are expected to be on the order of 10^5 man-rem per kg of tritium released to the environment. This dose would be small compared to unrestricted release of fission product and actinide inventories but is of sufficient size to be of public and regulatory concern.

3.3.5 Magnetic Field Materials Interactions

The presence of large magnetic fields may perturb the thermal response of hybrid reactor materials through minute variations in chemical equilibria, phase variations and transport properties. However, the tentative conclusion was that for the hybrid operating at a typical magnetic field of 10T, no effects would be anticipated.

3.4 SMALL FUSION-FISSION BLANKET SAFETY STUDY (3.16)

As part of LLL/GA/PG&E definition and conceptual design study for a small (20 MW(t)) fusion reactor, a fast spectrum hybrid blanket design option was considered. A very preliminary survey evaluation into the safety/siting aspects of the fusion and fusion-fission small reactor alternatives was included as part of the design study. Aspects of the small reactor siting study which may be extended to large hybrid safety are: lined or unlined but closed containments will most likely be required for hybrid applications,

continuously vented and filtered containments will not be possible. From the standpoint of radiological/ecological impact, the thorium blanket assembly is more attractive than uranium-blanket configurations. The use of a PCRV reactor containment structure has the potential of reducing the doses associated with the release of condensable fission products through plateout effects on inner PCRV surfaces.

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4. METHODOLOGY OF SAFETY ANALYSES

The safety evaluation of the fusion-fission hybrid reactor is certain to draw upon experience from the fission reactor industry. At the present time there are basically two methods of analysis that are employed in the safety evaluation of fission reactors and they are usually referred to as the deterministic method and the method of probabilistic risk assessment. It should be understood that these are not really two distinct methodologies but rather they are complementary techniques for safety analysis. The two methods are described below.

4.1 DETERMINISTIC SAFETY ANALYSIS

Historically, the deterministic method of safety analysis was employed first in the licensing of fission power reactors and consequently can be thought of as the conventional method. In the deterministic method of safety analysis the reactor plant is first studied to identify what conditions can lead to accidents that can cause harm to the public. The worst set of accidents are then selected for detailed analysis. Analytical models are devised to represent the accident situation using conservative assumptions wherever precise information is unavailable and whenever there is an option for the accident sequence to branch in several directions. Therefore, the results of the analyses tend to be upper bound estimates. Attempts are sometimes made to determine the range of uncertainty and thereby evaluate the degree of conservatism built into the analytical results.

The advantages of the deterministic method of safety analysis are that it does provide an evaluation of the worst situation and it has been successful in establishing an excellent safety record. The disadvantage is that the method has become somewhat formalized in the selection and treatment of

potential accidents and, therefore, does not consider the wide range of possible accident cases of relatively low consequence but rather high probability.

4.2 PROBABILISTIC RISK ASSESSMENT

The probabilistic risk assessment method has been developed and applied to fission reactor safety in order to attempt a complete evaluation of the hazards to the public from the nuclear power industry. The basis of the method is a logical scheme whereby all aspects of safety are considered and not just the postulated severe accident cases as in deterministic safety analyses.

The most well-known example of probabilistic risk assessment is the Reactor Safety Study (WASH-1400) also known as the Rasmussen report (4.1). The Reactor Safety Study reports on the results of a sizable effort to assess the societal risks from light-water reactors. Although there has been much discussion concerning some numerical results and certain specific statistical analyses in the Reactor Safety Study, the methodology used is fundamentally sound. This soundness has been confirmed by the Risk Assessment Review Group Report, also known as the Lewis report (4.2), which was ordered by the NRC in order to make a critical review of the Reactor Safety Study.

Other examples of the application of probabilistic risk assessment to evaluate reactor safety may be found in reports on the Clinch River Breeder Reactor Plant (4.3) and the High-Temperature Gas-Cooled Reactor (4.4).

The steps in performing a probabilistic risk assessment analysis of a reactor for the purpose of protecting the public are as follows:

- 1) Identify all potential means of causing harm to the public such as from radionuclides, toxic materials, electromagnetic fields, etc.

- 2) Identify the barriers which exist to safeguard the public from the materials and/or energy sources listed in Step 1.
- 3) Identify what anomalous initiating events might occur which could breach protective barriers.
- 4) Construct event trees, which are merely logic trees, to show the response of the system to an initiating event.
- 5) Determine the probability and consequence of the various branches of the event trees.
- 6) Scrutinize the results of Steps 4 and 5 for possible variations on the steps in the event trees.
- 7) Analyze the results of the preceding steps for the effect on the public.

Figure 4.1 illustrates the steps of the probabilistic risk assessment described above. The steps on the left-hand side of the figure tend to be qualitative analyses. The quantitative analyses are indicated by the two boxes labeled probability and consequence evaluation. The probability evaluation includes all the tasks needed to determine the frequency of occurrence of the various branches of the event trees. This involves applying reliability theory, compiling reliability data from applicable sources, evaluating the uncertainty on the computed probabilities and assessing the effect of potential common cause factors on the results.

The box labeled consequence evaluation represents all the tasks needed to determine the effect on the public of a given sequence of events. In the case of accidental release of radioactive species, this would include calculation of the radionuclide inventory, release rates from containment structures, the decay of radioactivity during transport, the effect of meteorological conditions, biological pathways and the effect of radionuclides on humans.

Fig. 4.1 Probabilistic risk assessment methodology

The boxes on the right-hand side of Fig. 4.1 represent the important final qualitative analysis and evaluation of the numerical results. The numerical results may be expressed as the risk to society where risk is defined as (4.1),

$$\text{risk} = \text{probability} \times \text{consequence}.$$

For example in the case of radioactivity, risk might be expressed in the units of REM^{*}/yr while probability would be in units of events/yr and consequences in REM/event. Risk may also be expressed in other units as well, for example \$/yr. A customary way to display the numerical results for evaluation is a graph of probability versus consequence.

The advantage of probabilistic risk assessment as compared to deterministic safety analysis is that probabilistic risk assessment considers the entire range of events from low probability and high consequence events to high probability and low consequence events and quantifies results so that the total risk may be evaluated. An uncertainty analysis is an integral part of the quantification process.

Another advantage of the probabilistic risk assessment method is its logical and systematic approach to evaluating safety. This systematic approach is equally valid with a new reactor system as well as a mature and highly developed system.

The disadvantage of probabilistic risk assessment is in regard to the availability of reliability data. There is a growing data bank of reliability data on generic equipment in use in various industries such as pumps, valves, motors, switches, etc. However, on a new concept such as the fusion-fission hybrid there will obviously be a lack of reliability data on special items of equipment. As a result the uncertainty band on some probabilistic calculations will be large.

^{*}REM = Roentgen equivalent man, a unit of biological damage of gamma radiation.

4.3 APPLICATION OF PROBABILISTIC METHODS DURING CONCEPTUAL DESIGN

The method of probabilistic risk assessment will lend itself very well to evaluating safety issues during the conceptual design phase of the hybrid reactor. This is because the logical framework is ideally suited to not only identifying the whole scope of safety problems but narrowing the problems down to the significant ones.

In the application of probabilistic risk assessment to the hybrid reactor and particularly during the conceptual design phase, the main advantages are that the methodology can be used to help evaluate various design options and can help identify where it would be advantageous to invest R&D effort on safety problems. These facets of probabilistic risk assessment are illustrated by the boxes on the right-hand side of Fig. 4.1 and are presently incorporated into the development program for the Gas-Cooled Fast Reactor (4.5).

Obviously during conceptual design there will not be sufficient design detail to perform an in-depth probabilistic analysis. However, the probabilistic methodology can be applied in a rough way at first and the analysis perfected as the hybrid reactor design evolves. A major advantage of this approach is that safety becomes an integral part of the design process. Not only will safety issues be given proper emphasis throughout the program but there will be assurance that costly design retrofit to satisfy safety needs will not have to be made late in the program. It is also possible to establish safety and reliability targets for various subsystems of the hybrid reactor to meet an overall safety goal thereby providing guidance to the designers on the safety requirements of systems under their responsibility.

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5. PRELIMINARY SURVEY OF HYBRID SAFETY ISSUES

During FY79, a preliminary survey of the safety issues affecting the fusion-fission hybrid reactor was made. It is perfectly clear that the main safety issue for the hybrid will be from potential hazards to the public. This is not to mean that occupational safety issues and the impact of the hybrid reactor on the environment are to be ignored. However, the first priority will be to address the question of public safety.

The primary hazard to the public will be from the accidental release of radioactivity to the environment. This is the same conclusion also reached in the case of the pure fusion reactor; see the references for Section 3. In the case of the fusion-fission hybrid reactor, the potential radioactivity sources are all those of the pure fusion reactor plus radioactivity sources in the fission blanket.

Another potential source of hazard to the public is the inventory of toxic materials, primarily lithium which will be used for breeding tritium and possibly as a coolant. There are other potential hazards to be included such as missiles produced by explosions, fires from various causes and the effect of electromagnetic fields.

Figure 5.1 illustrates the potential hazards to the public in the form of a fault tree diagram. Since fault tree diagrams will be used extensively in this section of the report, a short description may be useful at this point. Fault tree diagrams are used in probabilistic risk assessment as a logic tool to illustrate causes of failure which could lead to an undesirable event (called the top event) at the top of the diagram then developing below this other events which could lead to the top event. A number of symbols are used in fault tree diagrams to provide a rapid means of identifying the

Fig. 5.1 Potential hazards to the public

logic of events. The only symbols to be used in this report are defined below.

This symbol signifies a resultant fault event as the result of other events that occur below it.

The diamond is a basic event that will not be developed further.

The AND gate is used to show that events below the gate must all occur for the event above it to occur.

The OR gate is used to show that any of the events below the gate can lead to the occurrence of the event above the gate.

This symbol is a transfer and is used to simplify the fault tree which could otherwise become unwieldy.

In the following sections the primary safety issue of radioactive release to the public is developed.

5.1 IDENTIFICATION OF RADIOACTIVE SOURCES

There are four sources of radioactivity that contribute to the hazard potential of a hybrid reactor. These are fission products, actinides produced from the fissile and fertile materials, activation products produced from the structural and other non-fuel materials and tritium. The quantities of these four radioactive sources will vary widely depending on the specific details of a hybrid design. These radioactive sources are discussed below for typical fast-fission type "fuel and energy producing" hybrid reactors described in Section 2. For the "energy producing" hybrid, the fission product and actinide inventories may be higher; for the "fuel producing" hybrid, these inventories are expected to be smaller.

5.1.1 Fission Product Sources

Depending on the design option selected, either a uranium-plutonium or a thorium-uranium blanket breeding scheme may be employed in the fusion-fission hybrid. Regardless of which scheme is selected, neutron absorption in the bred fissile fuel will lead to fission product buildup in the blanket. The fission product inventories in the "mainline" fast-fission fusion-fission hybrid blanket, when compared on an equal energy production basis, are closely comparable to those observed in LWR pure fission cores (5.1). However, there are some minor differences, primarily in isotopic composition,

between hybrid and pure fission designs. These differences are attributed to the presence of the hard 14 MeV neutron spectrum from the hybrid's fusion neutron driver.

This high energy 14 MeV spectrum results in an increase in fission yields for fission fragment nuclides of nearly equal atomic mass, while for dissimilar massed fission fragments, the change is less pronounced (5.1). Additionally, the fission yield curves shift to the right (yielding higher atomic mass fission fragment nuclides) with increasing fissioning nuclear mass.*

The presence of (n,2n) and (n,3n) reactions above a neutron threshold energy can transmute many of the fission product radionuclides to less hazardous nuclides. In fact, this high energy "scavanging" reaction can serve to reduce the elevated quantities of many of the equal massed fission products resulting from the 14 MeV neutron spectrum.

Kastenberg, et al., have provided the only quantitative information to date on the rigorous consideration of the effects of both high neutron energy shifted fission yields and competing (n,2n) and (n,3n) reactions on the accumulated inventory of fission products present in fusion-fission hybrid blankets (5.2). The authors estimated the fission product inventories for selected biologically significant radionuclides under comparison conditions of 1) an LWR core operating for three years at 1000 MW(t), using an LMFBR spectrum, 2) a 1000 MW(t) UC_2 blanket fusion-fission hybrid blanket without consideration of (n,2n) reactions and 3) the same 1000 MW(t) hybrid blanket with consideration of (n,2n) reactions. For the above analysis conditions, the end-of-life fission product inventories have been extracted from the Kastenberg study and are reproduced in Table 5.1. The significant conclusion resulting from the comparison study was that the LWR and hybrid inventories did not differ significantly in nuclide quantities and character. Most severe and unanticipated irradiation fluxes of at least 10^{16} n/cm²-sec in the 10 to 14 MeV range would be necessary to alter this conclusion (5.2).

* A consideration in uranium versus thorium breeding blanket inter-comparisons.

For comparison purposes, Table 5.1 also contains radionuclide inventory information predicted for a LWR and a HTGR operating under a thermal neutron spectrum at a total power level of 1000 MW(t). With the exception of Ru-106 (lower thermal spectrum yield), the LWR and HTGR thermal reactor inventory estimates given in Table 5.1 are also found to be similar to the hybrid (fusion spectrum) and LWR (fast spectrum-LMFBR) estimates of Kastenbergl. This comparison then tends to support the earlier statement, that the fission product inventory of the fusion-fission hybrid reactor are truly similar to comparably sized LWR reactors. Further, apparently the HTGR fission product inventory may also be considered to be of similar character to a hybrid blanket operating at an equal thermal power level.

The discussion to this point has dealt primarily with uranium-based systems. At the present time, no information could be identified developing the fission product inventory for thorium-based fusion-fission hybrid blankets. If the thorium blanket option is to be pursued, future work in this area would be necessary.

Under accident conditions, the fission products present in the fuel element matrix of the hybrid blanket are expected to exhibit mobility and transport characteristics similar to LWR designs.

The fission product inventory depends upon the amount of fissions occurring in the blanket. For the typical fast-fission hybrid system, about 90% of the blanket energy is fission energy and the blanket lifetime is generally similar to that of a fission reactor. Hence, the quantity of fission products is expected to be quite similar to that of a fission reactor. For the fuel producing hybrid, it may be possible to suppress fission and thus suppress the formation of fission products such that the inventory, per unit energy, is greatly reduced.

5.1.2 Actinide Production

In addition to the production of fission products through fission, heavy nuclei undergo transmutation through neutron capture, leading to the

TABLE 5.1
FUSION-FISSION HYBRID FISSION PRODUCT INVENTORY, 1000 MW(t)
Fission Product Inventory, (Ci)

Radionuclide	LWR Core ^(a) 3-yr Operation, LMFBR Spectrum	Hybrid UC ₂ ^(a) Blanket Fusion Spectrum		HTGR, Thermal ^(b) Spectrum	LWR, Thermal ^(c) Spectrum
		Without (n,2n)	With (n,2n)		
Sr-89	2.39 + 07	2.55 + 07	2.07 + 07	4.87 + 07	2.94 + 07
Sr-90	2.59 + 06	1.97 + 06	1.66 + 06	2.57 + 06	1.16 + 06
Tc-99	4.77 + 02	5.00 + 02	4.75 + 02	3.41 + 02	(d)
Ru-106	1.82 + 07	2.06 + 07	1.69 + 07	2.32 + 06	7.81 + 06
I-131	2.87 + 07	2.67 + 07	2.60 + 07	2.87 + 07	2.66 + 07
Cs-137	3.60 + 06	3.44 + 06	2.57 + 06	2.49 + 06	1.47 + 06
Ce-144	3.70 + 07	3.22 + 07	1.81 + 07	3.41 + 07	2.66 + 07

(a) Data extracted from Ref. 5.2.

(b) Equilibrium Cycle 3150 MW(t) HTGR core of Ref. 5.3 normalized to power level of 1000 MW(t).

(c) 3200 MW(t) three-region PWR core of Ref. 5.4 normalized to power level of 1000 MW(t).

(d) Not reported in Ref. 5.4.

formation of various actinides. Actinides are characterized by half-lives of up to millions of years, accompanied by heavy alpha activity and high toxicity, and resulting in a long-lived biological hazard. An evaluation of the safety of a hybrid reactor necessarily requires the evaluation of the Biological Hazard Potential (BHP) associated with these nuclides.

In order to estimate the actinide inventory for both the uranium and thorium fuel cycles, a small computer code was written to perform a simple 3-group calculation of the production, consumption, and decay of the radioisotopes of atomic numbers 89 through 96. Reasonable agreement with other calculations (5.1, 5.5) of actinide production were achieved with the code. The major production pathways for the two cycles are shown in Figs. 5.2 and 5.3. A 3-group calculation was the minimum necessary in order to accommodate the difference in the neutron spectrum between a hybrid reactor and a conventional fast- or thermal-reactor. This difference is a high-energy peaking of the neutron flux resulting from thermonuclear source neutrons having much higher initial energy than fission source neutrons. In general, this difference is noted in suppressed neutron interaction (fission, capture) in the thermal region from the depressed low energy flux, and increased neutron interaction (multiple neutron emission) in the high energy regions from the enhanced high energy flux.

The relative magnitudes of these effects serve to decrease production of certain actinides in the hybrid to a level at which they do not contribute significantly to the overall BHP while increasing the production of others with the reverse effect. Examples of the former are Am-241, Cm-242, and Cm-244. Examples of the latter are Th-230 and -231, Pa-231 and -233, Np-239, and Pu-241. The numerical results of the calculations are presented in Table 5.2.

Table 5.2 presents MPC's (5.6) and BHP estimates for four conventional nuclear reactors obtained from radionuclide inventories reported in Refs. 5.7-5.10 and normalized to 1000 MW(t) for comparison to the hybrid. The BHP associated with the fertile material (^{232}Th or ^{238}U) are 5 to 6 orders of magnitude smaller than those of the bred actinides and are not

Fig. 5.2 Production chain for the major contributors to actinide BHP in the uranium cycle. (BHP normalized to 1000 MW(t) in parentheses.)

Fig. 5.3 Production chain for the major contributors to actinide BHP in the thorium cycle. (BHP normalized to 1000 MW(t) in parentheses.)

TABLE 5.2
MAJOR CONTRIBUTORS TO ACTINIDE BHP IN FISSION REACTORS AND THE
HYBRID REACTOR WITH THE URANIUM AND THORIUM CYCLES

	(a) MPC _{air}	(b) BHP (km ³ of Air/GW(t))						Ci Produced per Initial Metric Ton of Fuel, 30 GW-d/MT, 40 MW/MT	
Nuclide	(μCi/ml)	HTGR	LWR	LMFBR	GCFR	Th-Hybrid	U-Hybrid	Th-Hybrid	U-Hybrid
Th-228	2 - 13	1.8 + 6	1.6 + 2			7.0 + 7		5.5 + 2	
-230	8 - 14	1.6 + 4				6.9 + 5		2.2 + 0	
-231	4 - 8					3.6 + 5		5.8 + 5	
Pa-231	4 - 14	7.2 + 4				1.0 + 7		1.6 + 1	
-233	6 - 9					1.8 + 7		4.2 + 6	
U-232	9 - 13	2.3 + 6	2.1 + 2			8.2 + 7		2.9 + 3	
-233	4 - 12	4.7 + 5				3.4 + 6		5.4 + 2	
Np-239	2 - 8						2.5 + 8		2.0 + 8
Pu-238	7 - 14	9.6 + 8	1.3 + 9	4.0 + 9	3.2 + 9		1.8 + 9		5.1 + 3
-239	6 - 14	1.6 + 6	1.8 + 8	1.1 + 9	9.1 + 8		4.2 + 9		9.9 + 3
-240	6 - 14	2.5 + 6	2.6 + 8	1.2 + 9	9.6 + 8		1.8 + 9		4.4 + 3
-241	3 - 12			5.6 + 9	4.4 + 9		5.0 + 8		6.0 + 4
Am-241	2 - 13	1.5 + 5	1.5 + 7	2.1 + 8	1.7 + 8		5.0 + 6		4.1 + 1
Cm-242	4 - 12	7.5 + 6	3.4 + 8	2.7 + 8	2.2 + 8		4.7 + 7		7.6 + 3
-244	3 - 13	1.1 + 7	2.8 + 6	3.5 + 7	2.8 + 7		8.7 + 6		1.1 + 2
TOTALS		9.9 + 8	2.1 + 9	1.2 + 10	9.9 + 9	1.6 + 8	8.6 + 9		

(a) Data from Ref. 5.6.

(b) BHP - Biological Hazard Potential (km³/GW(t)) = $\frac{\text{Radionuclide inventory } (\mu\text{Ci/GW(t)})}{\text{MPC}_{\text{air}} (\mu\text{Ci/ml})} 10^{-15}$.

shown. The table shows that the actinide BHP of a hybrid reactor operating on the uranium cycle is slightly lower than that of either the GCFR or LMFBR. However, with the thorium cycle, the BHP is 1-2 orders of magnitude less than fast reactors and nearly one order of magnitude lower than thermal reactors. For the uranium cycle, the decrease in the Am and Cm nuclides noted above can be attributed to decreased resonance absorption by Pu-240 due to the depressed neutron population below ~ 10 keV. For the thorium cycle, these isotopes are not produced to any great extent due to decreased resonance absorption in the uranium isotopes preventing the actinide chain from extending significantly past U-235. The increased nuclides result from enhanced multiple neutron emission reactions. The net result is still a decrease in actinide BHP for the thorium cycle.

As will be shown in Section 5.1.5, the actinide BHP is seen to be a major contributor to the total BHP of a hybrid reactor. As hybrid designs evolve, multigroup calculations will be necessary to refine the calculations of the actinide concentrations. Particular attention will have to be paid to the epithermal neutron energy region just above thermal to the low resonance energy region (few eV to 10's of keV's) as this is the region of greatest sensitivity in determining nuclide production rates and chain development. The significant reduction in actinide hazard from the thorium fuel cycle certainly merits it further consideration in reactor design from a safety point of view.

5.1.3 Activation Products

The intense unattenuated 14 MeV flux striking the first wall of hybrid reactor will cause a large number of nuclear reactions in the structural and other non-fuel materials and will generate large quantities of activation products. During normal operation, these will not present a major source of radiation exposure, but during scheduled maintenance, component disposal/recycle, or in an accident condition, their release presents a radiation hazard. The risks associated with these activation products will depend largely on the materials composing the first wall and blanket structures.

First wall activation products for a hybrid reactor should not differ significantly from a pure fusion reactor (5.2). In addition, Ref. 5.11 indicates that the first wall and inner blanket regions, where the flux is hardest, account for over two-thirds of the total activity of this type in a fusion reactor. For these reasons, the activation product inventory for the hybrid reactor was assumed to be equal to that of a fusion reactor. The results of Ref. 5.13 were then normalized to 1000 MW(t) and are presented in Table 5.3. In addition, the activation product inventories calculated for the reactor of Ref. 5.12 are included for comparison. In general, 1.1–1.2 Ci/W of activity are generated at shutdown from this source, with a corresponding BHP on the order of 10^7 km^3 of air per GW_t .

Other sources of activation products are the neutral beam injectors as a result of neutron streaming, the vacuum system as a result of first wall erosion and deposition and divertor/collector inventories from both sources. These are expected to have BHP's lower than the blanket by factors on the order of 10^6 , 10^{12} , and 10^4 respectively (5.11).

Alternate blanket structure materials could lead to lower activation. Among those proposed are aluminum, vanadium, titanium, and ceramic materials such as graphite and SiC. Because of the larger amounts of radioactivity associated with the fission products and actinides of a hybrid blanket, there appears to be little incentive to pursue low activation structural materials for hybrid reactors.

5.1.4 Tritium Sources

For near-term fusion-fission hybrid reactors utilizing the D-T reaction, the hybrid's tritium requirements are expected to be similar to those of a pure fusion reactor. To sustain the D-T reaction, significant quantities of tritium will be in-circuit or stored on the reactor site. This tritium, while not as biologically significant as the majority of the blanket fission products, actinides or activation products, is nevertheless highly volatile, mobile and present in large quantities within reactor systems and support

TABLE 5.3
ACTIVATION PRODUCT INVENTORY

	MPC _{air} (ci/m ³)	ORNL DEMO ^a		GA FRM ^b	
		Activity (Ci/GW _t)	BHP (km ³)	Activity (Ci/GW _t)	BHP (km ³)
Cr-51	2×10^{-6}	8.8×10^7	4.4×10^4	1.1×10^8	5.5×10^4
Mn-54	4×10^{-8}	8.2×10^7	2.1×10^6	2.0×10^7	5.0×10^5
-56	5×10^{-7}	3.3×10^8	6.6×10^5	2.4×10^8	4.8×10^5
Fe-55	9×10^{-7}	3.2×10^8	3.6×10^5	1.2×10^8	1.3×10^5
Co-57	2×10^{-7}	1.0×10^8	5.0×10^5	4.0×10^7	2.0×10^5
-58	5×10^{-8}	2.8×10^8	5.6×10^6	2.2×10^8	4.4×10^6
-60	9×10^{-9}	1.2×10^7	1.3×10^6	5.2×10^6	5.8×10^5
Mo-99	2×10^{-7}	3.5×10^7	1.8×10^5	2.2×10^7	1.1×10^5
TOTAL		1.2×10^9	1.1×10^7	7.8×10^8	6.5×10^6

^aORNL DEMO - stainless steel and liquid lithium, 1700 MW(t), 5 yr operation, 1.21 Ci/W at shutdown. Above results normalized to 1000 MW(t), from Ref. 5.11.

^bGA Field Reversed Mirror - Inconel 718 and LiO₂ ~ 50 MW, 1 yr operation, 1.13 Ci/W at shutdown. Above results normalized to 1000 MW(t), from Ref. 5.12.

NOTE: V-52, Ni-57, Co-60m not included in table because MPC_{air} not evaluated for short half-life radionuclides.

equipment. For this reason, the risk envelopes of low consequence, high probability accidents or off-normal radioactivity releases are expected to be dominated by tritium considerations.

The tritium inventories of both the Westinghouse (5.13) and LLL/GA (5.1) fusion-fission hybrid designs were examined to develop a representative hybrid reactor tritium source for safety analysis studies. From the design information available, it was concluded that the LLL/GA concept has the most mature information on tritium system configurations and hence it was selected as representative of hybrid designs.

Table 5.4 summarizes the hybrid tritium inventory and its approximate partitioning into the hybrid reactor systems. This tabulation is for a normalized blanket thermal power of 1000 MW, and has been derived based on the LLL/GA design (5.1). Of the total site tritium inventory, retrievable storage (2.4 kg) and blanket breeding pins (7.9 kg) represent the largest fraction of on-site tritium, amounting to 95% of the total.

Production of plasma feed tritium is currently being considered under two design options, (1) continuous recovery of blanket bred tritium and (2) intermittent harvesting of the tritium from sealed blanket elements at the period of fissile fuel recovery. Estimates of blanket tritium inventories given to Table 5.4 are based on an intermittent breeding pin harvest, as this selection tends to conservatively maximize the site tritium inventory.

5.1.5 Comparison of Hybrid Reactor Radioactive Sources

A summary of the radioactive sources contributing to the hybrid reactor's biological hazard potential is given below.

<u>Source</u>	<u>km³ air/CW(t)</u>	BHP	
		<u>% of Total Uranium Blanket</u>	<u>% of Total Thorium Blanket</u>
Fission Products	5.7 + 08	6	75
Actinides (U)	8.8 + 09	94	---
(Th)	1.8 + 08	---	24
Activation Products	1.1 + 07	< 1	1
Tritium	5.5 + 05	< 1	< 1
TOTAL (U Blanket)	9.4 + 09	100	---
(Th Blanket)	7.6 + 08	---	100

With the uranium blanket, the bulk of the radioactive hazard to the public resides in the actinide inventory. However, this source is highly immobile and contained within the fuel structure. On the other hand, the

TABLE 5.4
FUSION-FISSION HYBRID TRITIUM SOURCE INVENTORY,
NORMALIZED TO 1000 MW(t) (a)

	Mass	Curies
Tritium in blanket ^(b)	7.9 kg	7.9 + 07
Tritium in storage (6-month supply)	2.4 kg	2.4 + 07
Tritium in active fuel systems		
Fuel purification-cryogenic distillation columns	0.42 kg	4.2 + 06
Cryopanel		
direct converter	60 g	6.0 + 05
neutral beam direct converter	75 g	7.5 + 05
Neutral beam-processor sieve line	8.5 g	8.5 + 04
Direct converter-processor sieve line	1.5 g	1.5 + 04
Reactor hall-processor sieve line	54 mg	5.4 + 02
Tritium in circulating secondary coolant	1.8 mg	1.8 + 01
TOTAL	10.9 kg	1.1 + 08

NOTES

- (a) Data extracted from LLL/GA mirror hybrid design, Ref. 5.1 and normalized to a blanket thermal power of 1000 MW.
- (b) Closed fuel pin breeding of tritium conservatively assumed, i.e., tritium bred in place and processed at time of fissile fuel harvest.

gaseous fission products and tritium, though not as biologically significant, are highly mobile and present in large quantities.

With the thorium blanket, the actinide inventory is significantly curtailed, making fission products the primary contributors to radiological hazard. The use of the low-consequence fission-suppressed blanket concept would result in a lower fission product inventory. The mobility of the fission products and tritium remains the same as for the uranium blanket.

The use of BHP is not intended to imply that these materials would actually be released and require such dilutions. Rather, it is a way of comparing the relative hazard of different materials with differing characteristics such as toxicity, half-life, etc. In fact, release mechanisms, pathways and probabilities need to be considered. Nonetheless, a major focus of the safety program is to quantify the hazards, as well as the release pathways and probabilities, in a meaningful way.

5.2 RADIOACTIVITY BARRIERS

Once having identified the sources of radioactivity in the fusion-fission hybrid reactor, the next step in the probabilistic risk assessment methodology is to identify the barriers which preclude the accidental release of radioactivity to the environment. Since the safety survey for FY79 is meant to consider the hybrid reactor in general terms, the identification of radioactivity release barriers must likewise be in general terms. It should be understood that the development in this report can only be considered as a preliminary assessment. The identification of release barriers must be refined as a firm hybrid design concept evolves.

Figure 5.4 illustrates the potential release barriers for accidental release of radioactivity to the environment. First consider Fig. 5.4A which shows the release barriers for radioactivity from the fission blanket. The first barrier to radioactivity release is the fuel structure itself which depends upon the chemical composition and physical state of the fuel. If, for example, the fuel is in the form of a metallic-oxide pellet similar to light-water reactor fuel, then the fuel bred from fertile material (U or Th) will be contained within the crystalline structure of the fuel pellet. Fission products will be contained within the crystalline fuel structure to a certain degree depending upon fuel temperature and irradiation exposure. Gaseous fission products will be most mobile followed by volatile fission products and lastly solid fission products. Fertile and fissile fuel as well as fission products will be contained within some form of fuel cladding either metallic or ceramic. If the fuel cladding barrier is breached, the radioactivity will still be contained within the structural boundary of the

Fig. 5-4 Radioactivity release barriers

E. TRITIUM RELEASE FROM REACTOR CHAMBER

F. TRITIUM RELEASE FROM VACUUM PUMP CHAMBER

G. TRITIUM RELEASE FROM TRITIUM BREEDING BLANKET

Fig. 5-4 (Continued)

Fig. 5-4 (Continued)

fission blanket referred to here as the primary coolant boundary. If the primary coolant boundary is also breached, there is still a secondary containment or merely a confinement vessel or possibly a combination of both. Another pathway to the containment is shown in Fig. 5.4A, namely from the primary coolant boundary to the fusion vacuum boundary and fusion coolant boundary. This pathway is to illustrate the possible design configuration where the fission blanket is built inside of the fusion vacuum vessel.

Another pathway for the release of fission blanket radioactivity shown in Fig. 5.4A is via the secondary coolant boundary. Here it is presumed that the radioactivity released into the primary coolant can physically enter the secondary coolant stream due to a failure of the secondary coolant boundary. This would necessitate, for instance, that the primary coolant pressure be greater than the secondary coolant pressure. From the secondary coolant boundary, radioactivity can either enter the secondary containment via an additional failure in the secondary coolant boundary or escape past isolation valves into the turbine building. Of course, the definition of the turbine building is speculative in this preliminary safety survey but in any case it is assumed that once radioactivity has past isolation valves that it is equivalent to having entered the atmosphere.

The accidental release of radioactivity induced in the coolant, assuming that induced coolant activity is indeed possible, is shown in Fig. 5.4B. This case is the same as the case of accidental release of fission blanket radioactivity once that radioactivity breaches the fuel cladding.

Radioactivity is induced in the structural materials of the fusion-fission hybrid reactor. If an accidental energy release occurs which melts or vaporizes some of the structural material, the activity has several barriers that must be penetrated before reaching the environment. Figure 5.4C shows several possibilities. One possible scenario is where a plasma disruption vaporizes some of the first wall in which case the resultant activity is contained by the fusion vacuum boundary. If that fails the primary coolant boundary provides a backup. If both of these are breached then the secondary containment provides retention. A more severe disruption can breach the

vacuum boundary after which the primary coolant boundary and secondary containment are still barriers to radioactivity release. Another possibility is the case shown as a dashed line in which the primary coolant boundary is not a barrier as might be the case if an energy release vaporized some part of the non-cooled vacuum boundary. A very severe case is where a large magnitude energy release vaporizes activated material external to the vacuum and primary coolant barriers making the secondary containment the only barrier remaining to protect the public. A final case is the one shown by a dash-dot line in Fig. 5.4C. This case represents the possibility that an energy release (e.g. magnet arcing) vaporizes some of the material of the primary coolant boundary though the radioactivity cannot escape without first breaching the fusion vacuum boundary and then the secondary containment.

There is the possibility that radioactivity can be induced in coolant corrosion products which can be relatively mobile. Figure 5.4D illustrates the barriers to the release of potential coolant corrosion products.

The effect of an accidental release of tritium has been treated in a number of studies (see Section 3) and the design of tritium systems has been given a fair amount of thought. In this report the tritium inventory has been assumed to be divided into five parts: (1) the tritium inventory directly connected with the fusion reactor and contained within the reactor chamber, (2) the tritium inventory associated with the vacuum pump system and located in the vacuum pump chamber which is separated from the reactor chamber, (3) the tritium contained in the tritium breeding blanket (which is actually also inside the reactor chamber), (4) the tritium processing facility which is assumed to be in an isolated area of the reactor building and (5) the tritium in the storage vault which is taken to be an isolated cell in the reactor building. These five parts of the tritium system are assumed to be connected by pipes via isolation valves. Further, these isolation valves are assumed to be automatic, fast-acting valves actuated by a tritium leak detection system. All tritium pipes and components are designed with double containment walls except for the main fusion vacuum vessel, neutral beam

injectors (if used) and the vacuum pumps. Finally, all of the tritium inventory is housed within the reactor secondary containment.

Figures 5.4E to 5.4I show the tritium release barriers. First looking at Fig. 5.4E, it is seen that tritium can be released to the secondary containment upon rupture of any of the fusion reactor component boundaries (such as the vacuum chamber, injectors or tritium piping) or fusion reactor component boundary plus the primary coolant boundary which are all within the reactor chamber. Further, tritium release will occur if both sets of isolation valves from the vacuum system and tritium processing system fail to close after the fusion vacuum boundary is breached.

The barriers to tritium release from the vacuum pump chamber are shown in Fig. 5.4F. Tritium will be released to the vacuum pump chamber if a rupture occurs in the vacuum pump itself. It would require a rupture of both walls of the double-wall piping to release tritium to the vacuum chamber. Isolation valves from both the fusion reactor chamber and tritium processing system would have to close to preclude further tritium release into the vacuum pump chamber. If the vacuum pump chamber was not designed to contain a tritium spill or if a leak developed, then tritium would be released to the secondary containment.

Figure 5.4G shows the barriers to tritium release from the tritium breeding blanket. Breaching of these barriers can be accomplished by either tritium permeation, or rupture of either the pin cladding or purge system tubing. Any of these failures could lead directly to tritium release into the primary coolant, for which the discussion of Fig. 5.4A subsequently applies. In continuous tritium processing schemes, purge system tubing failures coupled with failures of isolation valves could lead to tritium release into the secondary containment or tritium processing system chamber. In batch processing, the tritium-containing compound could be transported directly into the tritium processing system, or it can be removed off-site for processing. The evaluation of various design concepts for tritium

processing at this stage of development of the tritium breeding system would be an appropriate and worthwhile application of probabilistic risk assessment.

The release of tritium from the tritium processing facility, Fig. 5.4H, is similar to a release from the vacuum pump chamber with two exceptions. First, there are expected to be many more components and pipes in the tritium processing facility which can fail as compared to the vacuum system. If the tritium processing facility is not fully automated, the influence of human error would have to be evaluated. The second exception is that the tritium breeding and recovery system and the tritium storage vault will be connected to the processing facility via an isolation valve. In Fig. 5.4H, the connection from the storage vault is shown dotted to signify that the connection can be based on either a batch process or a continuous process.

The public is protected from a tritium release arising in the tritium storage vault by the same number of barriers as in the vacuum pump chamber and processing facility. One further barrier can be provided if tritium is contained as a chemical compound where release requires a chemical reaction. This can be accomplished, for example, by storing tritium as a metal hydride (or more properly as a metal nitride).

To summarize the results of identifying radioactivity release barriers shown in Fig. 5.4, it is seen that there are, in most cases, multiple barriers to protect the public from radioactivity. In the case of the fission blanket the number of barriers corresponds to the barriers found in fission reactors. There are fewer barriers for primary coolant activity and activated coolant corrosion products, but the amount of radioactivity in these areas is expected to be quite small compared to what is contained in the fission blanket. The radioactivity induced in structural components is not expected to be of concern as far as safety to the public is the issue except in the unlikely event the structure is vaporized due to a very large energy release.

Tritium, because of its biological hazard potential and its mobility, should have systems designed to conform to the multi-barrier concept of protection. The greatest inventory of tritium, upwards of 90%, will be

contained in the storage vault and there are several barriers to the release of tritium to the atmosphere. The secondary containment is the only barrier to release of tritium from the reactor chamber as a result of rupture of any of the ducts, energy input devices (e.g. neutral beam injectors) or the main fusion vacuum vessel and is, therefore, the weakest area from the standpoint of release barriers. A detailed analysis of containment concepts using probabilistic risk assessment methods would be a useful task to run in parallel with design efforts. This approach would show how safety had been considered in each step of the design.

5.3 ENERGY SOURCES

An important consideration in a general safety assessment of the hybrid reactor is a tabulation of energy sources which could potentially be accident initiators. Table 5.5 is a partial listing of important energy sources. This tabulation will require updating as a conceptual design of the hybrid reactor takes form. Some approximate values, taken from Ref. 5.14 and 5.15 are shown to indicate the magnitude of these energy sources.

Considering the fusion side of the hybrid reactor, the main energy sources are found in the magnetic fields and in the potential chemical reaction of lithium with other materials, primarily air and concrete. A number of studies have already been made (see Section 3) to determine the potential safety consequences from these energy sources.

Considering the fission blanket side of the hybrid reactor, the main energy sources are from the reactivity of the fissile material and from the energy of radioactive decay. The design of the hybrid should preclude all possibilities for the fission blanket attaining criticality even under gross blanket disruption. The decay heat from radioactivity decay of fission products must be removed by means of redundant and diverse decay heat removal systems just as is required for fission reactors.

There are energy sources which could be part of the fusion system or fission blanket system or both that must be given attention in an overall

analysis and these are listed under the category "other." Pressurized gas systems are likely to be present in the hybrid reactor and any inventory of chemicals should be scrutinized as a potential energy source.

TABLE 5.5
FUSION-FISSION HYBRID REACTOR ENERGY SOURCES

	Approximate Values (GJ per 1000 MW _e)
1. Fusion reactor (5.14, 5.15)	
Magnetic fields	200
Plasma kinetic energy	2
Plasma nuclear energy potential ^(a)	70
Vacuums	16
Lithium ^(b)	6×10^4
2. Fission blanket (5.15)	
Reactivity ^(c)	10^8
Radioactive decay energy	40
Blanket coolant under pressure	--
3. Other	
Pressurized gas	--
Chemicals	--

(a) If completely fusioned.

(b) For liquid lithium. If solid breeder used, virtually zero stored energy.

(c) If completely fissioned.

5.4 MEANS OF RADIOACTIVITY RELEASE TO THE PUBLIC

The fault tree format has been used in Figs. 5.5 to 5.13 to illustrate the ways in which radioactivity can be released to the public. Fault tree diagrams are usually developed down to the point where failures of specific components are identified but in the present case the fault trees are only

carried down to the point where general failure mechanisms are identified. This approach is in keeping with the general nature of the safety assessment made during FY79.

Figure 5.5 is an overview of the ways radioactivity might be released to the public if the fusion-fission reactor is introduced into the economy. There are five major categories which describe the means for activity release. The main category of radioactivity release is from the two reactor power plants: the hybrid reactor and the fission burner reactor which utilizes fuel bred in the hybrid. The category of radioactivity release entitled "fission fuel processing" in Fig. 5.5 includes all the activities associated with the blanket fuel away from the site of the hybrid or burner reactors. The processing activities are mining, fertile blanket fuel fabrication and bred blanket fuel reprocessing and refabrication.

The category entitled "fusion fuel processing" allows for the possibility that a tritium processing plant may exist outside of the hybrid reactor site. The other two categories in Fig. 5.5, radioactive material in transit and radioactive material disposal, are self-explanatory and should be included in a complete safety evaluation of a fusion-fission reactor economy.

The remaining discussion is an elaboration of the means for accidental release of radioactivity to the public from the fusion-fission reactor.

A separation in the ways radioactivity can be released from the hybrid reactor has been made, Fig. 5.6, to distinguish between possible accidents that originate from reactor operation and all other accidents that have to do with waste handling and fuel storage. The latter accidents are assumed to occur outside of the secondary containment. The AND gate in the logic chain of reactor related events indicates that both a failure of the secondary containment and a failure in the hybrid reactor must occur before radioactivity can be released to the environment. Secondary containment failures have been grouped under the broad categories of failures of the filter system, failures of isolation valves to close and structural failures. Another logic separation has been made in the fault tree diagram of Fig. 5.6 to

Fig. 5.5 Means of radioactive release to the public for a fusion-fission hybrid reactor economy

Fig. 5.6 Means of radioactivity release to the public from the fusion-fission hybrid reactor

differentiate between accidents arising from either the fusion side or the fission side of the hybrid reactor. Although it is logically redundant to include the diamond in Fig. 5.6 showing that radioactivity release can come from coupled fusion-fission events, it is done in this case to emphasize that coupled events can occur.

Under the category of fission reactor events in Fig. 5.6, there are three possibilities for radioactivity release: fission blanket activity release, primary coolant activity release and the release of activation products. These are all developed further in separate diagrams as indicated by the numbered triangles denoting transfer to another figure. Similarly, the release of activation products and tritium from the fusion side are developed further in other figures.

The development of the means of activity release from the fission blanket is shown in Fig. 5.7. In order for radioactivity to escape the fission reactor portion of the hybrid reactor, it is necessary that there be failures in both the fuel element (i.e. cladding) and the primary containment for the fission blanket. A general classification of failure events is listed under the box for primary containment failure. There are, of course, the possibility of stress failures, particularly if high pressures and high temperatures exist inside the primary containment. If the primary containment requires cooling, then failure of the cooling system can lead to structural failure. The possibility of a primary containment failure due to a major failure of the fission blanket assembly, such as a melt-down accident, must be considered. Another classification of failure event is the possibility of a failure from the fusion side of the hybrid, such as a massive failure of one of the magnetic structures, that could fracture the fission reactor primary containment envelope. This is an example of an event leading to a coupled fusion-fission radioactivity release. Finally, external events such as earthquakes, missiles, hurricanes, etc., are listed as possible causes for failure of the primary containment.

Referring back to Fig. 5.7, it should be recalled that it is necessary for the fission blanket fuel element to fail as well as the primary containment

Fig. 5.7 Fission blanket release events

in order that there be a release of activity from the fission reactor side of the hybrid. The logic chain for fuel element failure has been divided into the two most important categories, namely structural failures and all the events associated with power-to-coolant imbalances. The structural failures for the fuel element are similar to those for the primary containment, however, there are a couple of differences that should be mentioned. First, there is the need to insert and remove fuel elements from the fission blanket so the possibility of handling event failures (dropped fuel element) exists. Second, there are likely to be many, on the order of a thousand, fuel elements so a few failures due to manufacturing defects are likely. Third, since fuel elements will be cooled by a flowing coolant medium, consideration must be given to flow induced vibrations causing failures.

Under the category of power-to-flow imbalance events for the fission blanket fuel element, there are two further categories for failures: overpower events and heat removal events. All the overpower events arise from disruptions in the normal operation of the fusion side of the reactor except for the one category entitled neutron attenuation anomalies. This general failure event is meant, for example, to cover the case where neutron attenuator material normally existing between the plasma and the fission blanket is inadvertently omitted during fuel handling operations causing a local high neutron flux when operations resume.

The category of failures under heat removal events, Fig. 5.7, are similar to those that would be listed in a pure fission reactor such as the PWR, BWR, HTGR or LMFBR. The general failure events are those associated with the loss or reduced capability of the main cooling system, the auxiliary cooling system and the secondary heat removal systems that reject waste heat to the atmosphere. The cooling systems may be fully functional but the actual coolant may be lost so this possibility is also listed. The main external cause that can lead to an inability to remove heat is the loss of electric power on-site and off-site.

In one design option of the hybrid reactor, many small fuel element modules are contained within the fusion vacuum boundary. Each fuel element module consists of a bundle of fuel rods within a pressure vessel and the fuel element modules are individually cooled. For radioactivity to be released to the environment, the barriers shown in Fig. 5.4 must be breached. Therefore, to illustrate this design option, the top lines of Fig. 5.7 must be changed as sketched below.

The development of ways in which primary coolant activity can be released to the atmosphere is shown in Fig. 5.8. Any mechanical failure of the primary coolant boundary, for example from a fracture of the structure or a valve failure, can cause the leakage of primary coolant and consequently any induced activity in the coolant. If induced activity in the coolant is a significant source of radioactivity in the hybrid reactor, then a purification and/or rad-waste system will be designed into the plant and failures in these systems will have to be considered. Other event categories are the same as those discussed for the primary containment in connection with Fig. 5.7.

The ways in which activation products can be released is developed in Fig. 5.9. It is assumed that activity will be induced in structural components such as the fusion vacuum boundary as well as various internal components of the plasma containment and in corrosion products that develop in

the coolant system. Neither of these sources of radioactivity are mobile although corrosion products can possibly be somewhat mobile. Activation products in structural components can only be released as a result of melting and/or vaporization which would require large disruptions in normal operation of the plasma or fission blanket. Vaporization of structural material appears to be the only way radioactivity can be released to the public since melted material will be contained in the secondary containment and will eventually solidify and can be cleaned up. Corrosion products can be released as a result of the same category of events discussed under primary coolant activity release; see Fig. 5.8.

As shown in Fig. 5.10, the logic chain for the release of tritium is divided into the tritium breeding system and the tritium fueling system. This distinction may not be proper for some hybrid reactor designs and may have to be amended.

Figure 5.11 shows the development of the ways in which tritium may be released from the tritium breeding system. Tritium can either be released from the tritium breeding blanket or from the tritium processing system. For tritium to escape from the breeding blanket, both the tritium breeding blanket and the tritium blanket containment will have to fail. Another possibility shown as a dotted diamond in Fig. 5.11 is a release from a tritium blanket venting system, a possible design option that allows for the continuous processing of tritium from the blanket. On the tritium processing side, tritium can be released only if failures occur in both the tritium processing chamber and the detritiation system. The assumption is tacitly made here that a separate detritiation system, with detection and clean-up components, exist in each compartment of the tritium system. The separate detritiation system could in fact just be a branch of a central detritiation system for the entire plant.

The ways in which tritium can be released from the tritium fueling system is shown in Fig. 5.12. The logic of this fault tree diagram is consistent with the compartmentalization of the entire tritium inventory as discussed in Section 5.2. In addition the assumption is made that there is

Fig. 5.8 Primary coolant activity release events

a separate detritiation system (or branch of a central system) for each of the tritium compartments: vacuum pump chamber, tritium processing chamber and the tritium storage vault. The tritium processing chamber in the tritium fueling system may or may not be common with the one in the tritium breeding system. If tritium should leak from the reactor chamber as shown in Fig. 5.12, it can be detected and cleaned up by the detritiation system that is part of the secondary containment filtration system shown in the fault tree diagram of Fig. 5.6.

Figure 5.13 shows the classification of component failure events that tie into the fault trees for the tritium breeding and fueling systems,

Fig. 5.9 Activation product release events

Fig. 5.10 Means of tritium release events.

Figs. 5.11 and 5.12. These component failure events have been discussed in connection with other parts of the hybrid reactor and do not require further elaboration.

In summary, it can be seen that the component failure event categories occur throughout the entire hybrid reactor plant. Many of the failure events are the same ones that should be considered in a safety evaluation of any reactor plant and indeed any fabrication/processing facility. The special failure events for the hybrid reactor are, of course, the events that arise from disruptions in the fusion side and fission side of the reactor. The unique feature of the hybrid reactor is the possible coupling of the fusion and fission failure events that could lead to situations not encountered by either one separately.

Fig. 5.11 Means of release from the tritium breeding system

Fig. 5.12 Means of release from the tritium fueling system.

Fig. 5.13 Component failure events

5.5 ACCIDENT INITIATING EVENTS

One of the most important steps in a complete safety analysis is the identification of accident initiating events. In order to do this it is first necessary to have a thorough understanding of the hybrid reactor design in terms of normal operation, maintenance, off-design performance and so on. However, a general classification of accident initiating events can be made for the hybrid reactor even during the pre-conceptual design phase just from a theoretical knowledge of the design. Obviously the classification of events will be general at this time and a most important aspect of the future safety program will be to review the list and add detailed information to make the classification of events specific to the design under study.

Table 5.6 is a general classification of accident initiating events arranged under the broad headings of fusion reactor, fission blanket, plant operation and external events. The headings have been chosen to be consistent with the development in previous sections. All of the events are self-explanatory or have been discussed previously. The possibility of human error exists throughout the entire cycle of design, construction and operation but has been listed under the plant operation heading in order to give recognition to this factor.

As the safety analysis proceeds on the hybrid reactor, the accident initiating events of Table 5.6 will be expanded particularly under the headings of duty cycle and faulted events. In addition, estimates will be made to determine the frequency of occurrence as, for example, the number of power trips, loss of vacuum, coolant system outages, etc.

5.6 EVENT TREES

The final analysis steps in the probabilistic risk analysis method are the development of event trees and the quantification of the probability of occurrence, the consequence, and the uncertainty of each event, permitting the construction of a risk plot with which to evaluate risk; see Section 4.

TABLE 5.6
FUSION-FISSION HYBRID REACTOR ACCIDENT INITIATING EVENT CLASSIFICATION

Fusion Reactor

1. Plasma events: power excursions, disruptions
2. Plasma heating device events
3. Magnet disruptions
4. Vacuum/cryogenic system failures
5. Cooling system failures
6. Tritium system failures: breeding, fueling, processing, storing
7. Mechanical failures: vessels, pipes, pumps, valves, etc.
8. Fires/explosions/missile generation

Fission Blanket

1. Neutron attenuation anomalies
2. Fuel handling events: refueling, shuffling
3. Loss of heat removal capability: system failures, flow blockages
4. Mechanical failures: cladding, vessels, pumps, heat exchangers, etc.
5. Fires/explosions/missile generation

Plant Operation

1. Duty cycle events
2. Faulted events
3. Control and instrumentation system failure events
4. Maintenance and repair events
5. Human errors

External Causes

1. Loss of off-site power
2. Earthquakes
3. Tornados
4. Floods/tsunamis
5. Fires/explosions/missiles
6. Sabotage

These steps of the method cannot be made until a conceptual design of the hybrid reactor takes form. The more detailed the design becomes, the more accurate the assessment of risk will be. However, even in the early phases of the conceptual design there is value in developing event trees to evaluate safety problems and there is particular value in using event trees to compare the risk of different design options. In the early phase of the design the event trees will be rather abbreviated to highlight only the major factors in an accident sequence and such event trees are sometimes referred to as pruned trees.

An example of an event tree is given in Fig. 5.14 but before discussing this case a few definitions and conventions about event trees should be covered. An event tree is a logic diagram that is a visual means for describing an accident sequence. By custom, the event tree is developed from left to right as depicted below. Each separate event in the chain of

events is represented by a branch with success (S) the upper leg and failure (F) the lower leg. At each branch either a success or a failure can occur and clearly this means that when there are many event sequences in the accident the diagram can be quite large. However, many of the branches can be omitted if they do not add useful information. For example, if the event tree given above describes an accident where radioactivity can be released and the first branch is the success or failure of the first barrier containing radioactivity, then success means no failure of the first barrier and consequently no release regardless of what other failures might occur.

Fig. 5.14 Event tree for tritium release from the reactor chamber

Therefore, the entire upper part of the event tree can be omitted except for the uppermost success path. Physical reasoning is the determining factor in deciding what can be omitted from an event tree. By custom, the final event tree is drawn as shown in Fig. 5.14 with failure branches dropped down from the success branches which are carried out as straight lines.

It is good practice in displaying event trees to describe each event on the diagram in sufficient detail to clearly indicate what is meant. A useful feature is to include an identification (ID) for each sequence string on the event tree. Finally, including the probability of failure at each branch and also including columns showing the probability of each sequence string and the consequence of each sequence makes the event tree a complete description of the results of a given initiating event.

The probability of failure, represented by the symbols P_i in Fig. 5.14, is nearly always a small number less than 10^{-2} so the probability of success, which is equal to $1 - P_i$, is rounded off to a value of one and omitted from the event tree. The probability of any sequence string is found by assuming each branch to be independent and applying the rule of probability for combined events which states that the combined probability is the product of the individual probabilities. If the events are strongly interdependent, then rules of probability for conditional events should be used.

With this brief introduction to event trees it should be possible to easily follow the logic of the event tree given in Fig. 5.14. First it must be emphasized that the example of tritium release from the reactor chamber is a hypothetical case and is only included to complete the presentation of the method of probabilistic risk assessment. Although the case is hypothetical, the sequence of events are still fairly realistic.

In the hypothetical event tree of Fig. 5.14, it is assumed that the initiating event is a large magnitude earthquake which has a probability P_1 of occurring. If the reactor chamber is not breached there is no possibility of a tritium spill and there is, obviously, no release of radioactivity to the atmosphere. This is the sequence of events identified by the branch AA.

Branch AB in Fig. 5.14 includes the condition that the vacuum boundary in the fusion chamber has been breached and tritium may enter the secondary containment but since the containment isolation and detritiation system works as designed, there is no radioactivity release to the atmosphere. The tritium in the secondary containment will eventually be removed by the detritiation system.

In branch AC, the conditions are that the initiating event caused a failure in the vacuum boundary of the fusion reactor which was detected so the reactor chamber was isolated from the remaining tritium inventory by closing automatic block valves. The inventory of tritium in the reactor chamber will eventually diffuse into the secondary containment. The secondary containment is isolated but the detritiation system in the secondary containment fails. Therefore, there is a tritium release to the atmosphere which is delayed from the time the earthquake occurred due to the time lag for tritium to diffuse out of the fusion reactor and the time lag for tritium to diffuse past the secondary containment filter system.

Branch AD is similar to branch AC except the secondary containment isolation functions fail so the same amount of tritium as in case AC is released to the atmosphere but the release is faster.

If the plasma isolation valves fail to close, then all of the tritium in the system, except perhaps the inventory in the tritium storage vault, will be released to the secondary containment. If the secondary containment is isolated and the detritiation system functions, there is no release to the atmosphere: branch AE. If the detritiation system fails, there will be a delayed release: branch AF. If the secondary isolation valves fail, the release to the atmosphere will occur quicker: branch AG.

The branches AH, AJ and AK are similar to the cases described above but here it is assumed that the tritium leak detection system fails to detect a tritium spill so the automatically actuated plasma blocking valves are not closed. The same amount of tritium leaks to the secondary containment

in cases AE, AF and AG and cases AH, AJ and AK since a failure of the tritium leak detection system is equivalent to the plasma isolation valves failing.

The largest releases of tritium to the atmosphere in the hypothetical event tree of Fig. 5.14 are from branches AG and AK with probabilities $P_1 P_2 P_4 P_5$ and $P_1 P_2 P_3 P_5$, respectively. The accident sequence branch with the greatest probability depends upon the respective values of P_3 and P_4 .

One of the main efforts in FY80 and subsequent years will be to develop event trees for the more important accident initiators. The degree of detail in the event trees will, of course, depend upon the degree of development of the hybrid design.

5.7 CONSEQUENCE ANALYSIS

It is recognized that the total radiological risk associated with the fusion-fission hybrid design is dependent upon normal operations, upset conditions, and accidents of various probability of occurrence and consequence severity. A balanced evaluation of the total risk spectrum of a given hybrid design would then require an evaluation of the consequences associated with normal operations and with accidents increasing in severity up to and beyond the design basis event. However, the hybrid designs at this time are not sufficiently detailed to permit rigorous consideration of the total spectrum of plant accidents. As the design matures and more design information becomes available, rigorous deterministic and probabilistic analysis can take place. For the present, we will limit this consequence analysis to the study of bounding accidents for the hybrid design. These severe bounding accidents define the upper bound envelope of risk/consequence to the population and environment surrounding the hybrid site.

The preliminary survey of hybrid safety issues (Section 5.0) identified the primary hazard to the public as being the accidental release of radioactivity to the environment. While non-radiological toxic material hazards,

hazards of explosions, fire from various causes and the effect of electromagnetic fields are of importance, the radiological inventory hazard is felt to dominate the hybrid risk profile.

5.7.1 Bounding Accident Scenario

Hybrid reactor safety studies reviewed to date (see Section 3) confirm the vulnerability of the hybrid's fission blanket to heatup and fuel damage in the event of blanket cooling loss. For moderate blanket fertile fuel residence times, criticality can apparently be ruled out as a hybrid safety concern (5.2). It follows that unrestrained blanket heatup may, in fact, be the event which bounds the release of radionuclides from the blanket to the containment. It is felt that, for the hybrid, the condition of loss of blanket cooling capability with no resumption of primary or secondary flow, represents a bounding condition similar to the LWR Class 9 event or the HTGR unrestrained core heatup event.

The power densities in the hybrid fissile fuel are similar to those in LWRs, in the range of $100\text{--}500\text{ W/cm}^3$ (5.2). Without cooling, the blanket can be expected to heat up rapidly, due to the fission product and first wall decay heat sources, eventually melting fuel and cladding which then slump and flow to the bottom portion of the reactor's containment. Helium-cooled blankets without cooling can be expected to begin melting in the range of 100-200 seconds, liquid-metal-cooled blankets would be expected to delay initial blanket melting for only a few hours (5.2).

5.7.2 Activity Release from Blanket

To develop a detailed estimate of the timing of the release of blanket radionuclides to the containment as well as the quantities released is beyond the scope of this study. A number of uncertainties surrounding the hybrid blanket meltdown process such as chemical forms present in the melt, volatility considerations, timing, fission product escape pathways and structural behavior are but a few considerations which confound estimates of hybrid blanket radionuclides release. Future work should focus on the estimation

of blanket radionuclide release fractions under heatup conditions. For this study, the blanket to the containment radionuclides release fractions will be simply selected to be consistent with those postulated for the LWR siting event, i.e., 100% release of noble gases (including tritium), 25% of the halogens and 1% of the remaining material* (5.16). Intuitively, this assignment seems reasonable, as the LWR and hybrid have nearly identical fission product inventories, fuel form and operational power densities and, hence, similar melt/release characteristics are expected.

5.7.3 Source Term

Sections 5.1.1 through 5.1.4 of this report develop information on the hybrid reactor's radiological inventory by estimating radionuclide quantities in the categories of tritium, activation products, fission products and the actinides. Table 5.7 summarizes this hybrid radionuclide inventory information for selected biologically and ecologically significant radionuclides.

Upon examination of the BHP's for the uranium or thorium blanket options (see Table 5.9), it is evident that the uranium blanket at End of Life (EOL) has a composite BHP approximately 12 times greater than for a thorium blanket of similar thermal characteristics. Additionally, the primary radiological hazard in the uranium blanket resides in the actinides produced, while fission products dominate in terms of radiological hazard in the thorium blanket.

5.7.4 Accident Conditions

Parameter selections and assumptions utilized in the bounding analysis were patterned after conservative assignments typically made in fission reactor site suitability studies. Where specific design information was not available (e.g., specific meteorological dispersion conditions or the nominal atmospheric leak rate of the containment), suitability conservative values were assigned based on engineering judgment.

* Bred fuel has conservatively been included in the 1% "other" fraction. It must be noted, however, that with proper design guidance, mechanisms for the 1% release of the remaining material may not be identifiable for the hybrid reactor.

TABLE 5.7
FUSION-FISSION HYBRID REACTOR RADIOACTIVE HAZARD INVENTORY

Summary Listing Significant Radionuclides ^(a)		
Radionuclide	Activity ^(a) (Ci)	BHP ^(b) (km ³)
Tritium Inventory		
H-3 Blanket	7.9 + 07	4.0 + 05
H-3 Retrievable Storage	2.4 + 07	1.2 + 05
H-3 Active Fuel Systems	<u>5.7 + 06</u>	<u>2.9 + 04</u>
Total	1.1 + 08	5.5 + 05
Activation Product Inventory		
Mn-54	8.2 + 07	2.1 + 06
Mn-56	3.3 + 08	6.6 + 05
Fe-55	3.2 + 08	3.6 + 05
Co-57	1.1 + 08	5.0 + 05
Co-58	2.8 + 08	5.6 + 06
Co-60	1.2 + 07	1.3 + 06
Mo-99	<u>3.5 + 07</u>	<u>1.8 + 05</u>
Total	1.2 + 09	1.1 + 07
Fission Product Inventory		
Sr-89	2.1 + 07	7.0 + 07
Sr-90	1.7 + 06	5.7 + 07
Ru-106	1.7 + 07	8.5 + 07
I-131	2.6 + 07	2.6 + 08
Cs-137	2.6 + 06	5.2 + 06
Ce-144	<u>1.8 + 07</u>	<u>9.0 + 07</u>
Total	8.6 + 07	5.7 + 08

TABLE 5.7 (Continued)

Summary Listing Significant Radionuclides ^(a)		
Radionuclide	Activity ^(a) (Ci)	BHP ^(b) ₃ (km ³)
Uranium Blanket Option		
Np-239	5.0 + 09	2.5 + 08
Pu-238	1.3 + 05	1.9 + 09
Pu-239	2.5 + 05	4.2 + 09
Pu-240	1.1 + 05	1.8 + 09
Pu-241	1.7 + 06	5.7 + 08
Am-241	9.7 + 02	4.8 + 06
Cm-242	1.9 + 05	4.8 + 07
Cm-244	<u>2.7 + 03</u>	<u>9.0 + 06</u>
Total	5.0 + 09	8.8 + 09
Thorium Blanket Option		
Th-228	1.4 + 04	7.0 + 07
Pa-231	4.1 + 02	1.0 + 07
Pa-233	1.0 + 08	1.7 + 07
U-232	7.5 + 04	8.3 + 07
U-233	<u>1.3 + 04</u>	<u>3.2 + 06</u>
Total	1.0 + 08	1.8 + 08

(a) All Hybrid Radioactive Inventory results reported have been normalized to a blanket thermal power of 1000 MW(t).

$$(b) \text{BHP-Biological Hazard Potential (km}^3\text{)} = \frac{\text{Radionuclide inventory } (\mu\text{Ci})}{\text{MPC}_{\text{air}} (\mu\text{Ci/cm}^3)} 10^{-15}$$

A detailed summary of the reference conditions, analysis parameters and assumptions used in the evaluation may be found in Table 5.8. Taken in total, these reference conditions are felt to provide a suitably conservative data base for bounding the hybrid reactor's consequence potential.

5.7.5 Dose Consequence Model Description

For the hybrid bounding accident investigated, dose consequences to the off-site population were developed utilizing the computer code TDAC (5.18). External plume submersion whole-body exposure and internal inhalation-dose commitment to the organs, lung, gastrointestinal tract, bones and total body were estimated for both the uranium and thorium blanket configurations studied.

The inhalation-dose commitment "effectivities," defined in Appendix A of Ref. 5.18, were used with the following exceptions: the tritium and actinide effectivities were extracted from the adult inhalation dose factors provided in Table E-7 of Ref. 5.17. The inhalation effectivities for the activation product radionuclides were developed using the methodology detailed in Appendix B of Ref. 5.18.

TABLE 5.8
HYBRID REACTOR - CONSEQUENCE BOUNDING ANALYSIS, LOSS OF COOLANT AND FLOW.
LIST OF PARAMETER SELECTIONS AND ASSUMPTIONS

Parameter	Assumption
Hypothetical accident examined.	Loss of Coolant and Flow (LOCAF), no auxiliary cooling employed.
Initial radioactivity inventory present in the reactor at the time of the accident.	See Table 5.7
Site suitability source release	
<u>Release Fraction</u>	<u>Fraction of initial Inventory Released to Secondary Containment Atmosphere</u>
<u>Material</u> - Tritium	100%
Noble gases	100%
Halogens	25%
Others (includes bred fuel)	1%

TABLE 5.8 (Continued)

Parameter	Assumption
Release Mode to Secondary Containment	Instantaneous release of inventory fraction to the secondary containment atmosphere at time = 0
<u>Secondary Reactor Containment</u>	
Containment leak rate	0.1% vol/day (lined)
Containment integrity	Maintained for the duration of the accident
Engineered containment atmosphere cleanup system characteristics	
Tritium	No air detrutiation system employed.
Others	Recirculation cleanup system assumed operational at initiation of the event. Flow rate of 1. vol/hr. assumed. Filter efficiencies of 0% for noble gases and tritium and 99% for all other materials were employed.
Natural deposition mechanisms (i.e., fallout and plateout)	Conservatively ignored
Reference site meteorology conditions assumed	

Atmospheric Dispersion Factor, X/Q (sec/m^3)⁽¹⁾

Distance (M)	0-8 Hour ⁽²⁾	8-24 Hour	1-4 Days	4-30 Days
100	3.4-02	9.0-03	3.2-03	8.0-04
200	1.0-02	2.6-03	9.0-04	2.1-04
300	5.0-03	1.2-03	4.3-04	1.0-04
500	2.1-03	4.8-04	1.7-04	4.0-05
2500	1.6-04	3.6-05	1.2-05	2.6-06

(1) Basis of atmospheric dispersion estimate; U.S. NRC Regulatory Guide 1.3, ground level release.

(2) A building wake correction factor of 3 should be included for the 0-8 hr. interval at the distance of 100, 200, 300 and 500 meters.

TABLE 5.8 (Continued)

Parameter	Assumption
Dose computation	
Breathing rates assumed	
<u>Time Interval</u>	<u>Breathing Rate Assumed (m³/sec)</u>
0.8 hr	3.47-04
8-24 hr	1.75-04
1-4 day	2.32-04
4-30 day	2.32-04
Inhalation dose commitment effectiveness	Ref. 5.17 adult inhalation values used. (Note: Ref. 5.17 has increased the tritium inhalation dose commitment factors by 50% to account for transpiration pathway. Also activation product effectivities developed using Appendix B of Ref. 5.18 information.)
Wind speed assumed	1.0 m/sec.
Decay and buildup enroute to dose receptor	Considered
Exposure pathways examined	Prompt inhalation and submersion in the passing plume only.
Dose computation computer program	TDAC/E1 (Ref. 5.18)
<u>Accident Mitigation</u>	
Continuous residency, i.e., no evacuation, of the exposed population is assumed.	

5.7.6 Results of Bounding Consequence Calculations

Table 5.9 summarizes the dose estimates for the hybrid blanket heat-up event. Both uranium and thorium breeding blankets have been included.

Additionally, Table 5.9 also includes LWR dose levels specified by the 10CFR100 siting event. No documented legislation or guidance specific to the siting of commercial fusion-fission central power stations has been prepared by U.S. agencies. However, realistically, it is safe to assume any future guidance governing hybrid plant operations will, as a minimum, be as stringent as those of the current-day fission power industry. Therefore, LWR reactor site criteria 10CFR100 dose limits will be used as a comparison point for the derived uranium and thorium hybrid blanket results.

The following observations are made relative to the consequence results report in Table 5.9:

- (1) The tritium dose is negligible by comparison to fission and activation product inventory contributions.
- (2) Activation product radionuclides contribute approximately 25% of the total lung inhalation dose.
- (3) Fission product radionuclides contribute all the thyroid dose commitment.
- (4) The actinide inventory for the uranium blanket dominates the bone dose category. (Plutonium isotopes contribute 95.7% of the reported dose.) Additionally, the bone dose of 290 rem exceeds the 10CFR100 limit by approximately a factor of 2.
- (5) From the standpoint of radiological considerations, specifically bone dose, the thorium hybrid blanket is more attractive than the uranium-blanket counterpart.
- (6) Both blankets were evaluated in a secondary containment structure leaking to the environment at a nominal leak rate of 0.1%/day. This leak rate is representative of a modern LWR lined containment. Since the resultant consequences for either blanket design are close to 100CFR100 limits with the lined design used, it is

TABLE 5.9
HYBRID REACTOR - BLANKET HEATUP CONSEQUENCE BOUNDING ACCIDENT

Radionuclide Category Identification (Fraction Released to Containment Building)	0-2 Hour Integrated Dose (Rem), at Dose Receptor Located at 500 meters				0-30 Day Integrated Dose (Rem), at Dose Receptor Located at 2500 meters			
	External Whole Body Gamma	Inhalation			External Whole Body Gamma	Inhalation		
		Thyroid	Bone	Lung		Thyroid	Bone	Lung
10CFR100 LWR siting event dose limits ^(a)	25	300	150	150	25	300	150	150
<u>Thorium blanket</u>								
100% Tritium blanket inventory	0	0.33	0.33	0.33	0	0.78	0.78	0.78
1% Activation product inventory	0.052	0	0.084	5.4	0.013	0	0.023	1.5
1% Fission product inventory ^(b)	0.015	83.	4.2	5.0	0.0042	23.	1.2	1.4
1% Actinide inventory	<u>0</u>	<u>0</u>	<u>1.1</u>	<u>3.1</u>	<u>0</u>	<u>0</u>	<u>0.3</u>	<u>0.83</u>
Total thorium blanket	0.067	83.0	5.7	14.0	0.017	24.0	2.3	4.5
<u>Uranium blanket</u>								
100% Tritium blanket	0	0.33	0.33	0.33	0	0.78	0.78	0.78
1% Activation product inventory	0.052	0	0.084	5.4	0.013	0	0.023	1.5
1% Fission product inventory ^(b)	0.015	83.	4.2	5.0	0.0042	23.	1.2	1.4
1% Actinide inventory	<u>0</u>	<u>0</u>	<u>290</u>	<u>10.</u>	<u>0</u>	<u>0</u>	<u>78.</u>	<u>2.8</u>
Total uranium blanket	0.067	83.	290	21.	0.017	24.	80.	6.5

^(a) In a letter (Ref. 5.19) to the CRBR, the NRC provided dose guidelines during construction (PSAR) of whole body 80%, thyroid 50%, lung 10%, and bone 10% of the 10CFR100 limits.

^(b) I-131 assigned a release fraction of 25%, remaining particulate fission products 1%.

doubtful if an unlined or more "leaky" containment would be tolerated in the hybrid programs. In fact, it is possible that perhaps a double containment option may be necessary if the assumed source term of 1% of the accumulated fuel activities is indeed applicable.

5.7.7 Summary

For the hybrid reactor, a most severe accident scenario was examined to bound conservatively the potential consequences of reactor accidents. The selected accident for the hybrid was the loss of blanket cooling capability with no resumption of primary or secondary cooling flow. This accident has many of the characteristics of the LWR core melt accident analyzed in WASH 1400.

Some aspects of the hybrid blanket's meltdown process, such as chemical forms present in the melt, volatility considerations, timing and progression of the event and fission product escape pathways are not fully understood. To account for these uncertainties radionuclide release, from the hybrid blanket, was conservatively assigned the release fractions associated with the LWR siting event; i.e., 100% accumulated noble gases and tritium, 25% of halogens and 1% of remaining material.* Accident conditions, parameter selections and assumptions were selected to lie on the conservative side, insuring a conservative bounding assessment of the hybrid's consequence potential.

Results indicate that fission product radionuclides and bred fuel contribute the majority of the meltdown consequence potential. This was not unexpected when the BHPs of tritium, activation products, fission products and actinides are examined.

With the exception of the actinide release dose component, the estimated hybrid blanket heatup doses are comparable to LWR values for the siting event.

* Bred fuel conservatively included in this 1% category. It is again noted that with proper design guidance, mechanisms for this 1% release may not be identifiable for the hybrid reactor.

Again, this was not unexpected as the hybrid's inventory is roughly the same as the LWRs and the radionuclide release has been assigned to be identical to the LWR TID-14844 fractions.

The uranium blanket with its attendant bred plutonium inventory, is significantly more radiologically limiting when compared to thorium blankets. From Table 5.9 it is observed that the inhalation bone dose commitment for the uranium blanket is a factor of approximately 50 greater than the thorium counterpart. This more favorable radiological aspect of the thorium blanket over the uranium blanket should be examined more fully and exploited.

It is anticipated that significant reductions in radiological risk could be afforded by the use of fission suppressed blankets. Especially those employing thorium breeding based systems. Reduction in radiological risk would come about due to (1) a reduced severity blanket heatup transient - perhaps developing over a period of days and (2) the reduction of fission products built up in the blanket itself due to fertile material choice and online reprocessing.

5.8 SUMMARY OF FY79 WORK

The work performed during FY79 and discussed in Section 5 is primarily a preliminary safety survey of the fusion-fission hybrid reactor upon which to base the proposed hybrid safety program plan. Several conclusions can be made as a result of the safety survey:

- For uranium-based breeding blanket systems, the fission product inventory of the fusion-fission hybrid is similar to comparably sized LWR reactors. Under blanket melting conditions, the fission products are expected to exhibit mobility and transport characteristics similar to LWR designs.
- No information could be identified which developed the complete fission product inventory for thorium-based fusion-fission hybrid blankets with proper consideration of $(n,2n)$ and $(n,3n)$ reactions

as well as 14 MeV neutron fission yields. Future work in this area would be beneficial.

- The hybrid operating on the uranium cycle produces an actinide BHP on the same order of magnitude as the LMFBR and GCFR. On the thorium cycle however, the BHP is reduced by two orders of magnitude below the two fast reactors and nearly a full order of magnitude below thermal reactors.
- The pursuit of the low-consequence fission-suppressed hybrid blanket concept could conceivably reduce the actinide BHP an additional one or two orders of magnitude while maintaining a high fissile production to thermal power production ratio and therefore appears to be a worthwhile venture.
- Activation product BHP's approximate those of pure fusion and do not significantly contribute ($\approx 1\%$) to the hazard potential of the hybrid.
- The tritium inventory present in the hybrid design is not as biologically significant as the majority of the blanket fission products, actinides or activation products, however, it is highly volatile, mobile and present in large quantities within the reactor systems and support equipment. As a result, the risk associated with relatively low consequence but potentially high probability accidents should be considered.
- Tritium and gaseous fission products in the blanket are the most mobile radioactivity sources and, in most cases, there are several barriers that must be breached before radioactivity can be released to the environment. However, if the fusion vacuum boundary or any of the tritium injection system piping is breached in the reactor chamber, the only barrier to release of radioactivity is the secondary containment. Therefore, a probabilistic risk assessment of various secondary containment concepts would be a useful task.

- It is recommended that a task be undertaken to determine the rate of diffusion of tritium from various components of the fusion reactor. This information is needed to determine the necessary rate of isolation valve actuation to preclude tritium release from parts of the system away from the failure point. The information is also needed to evaluate detritiation system performance requirements.

This recommendation would also apply to pure fusion safety studies but is included in the hybrid area because, though not quantified in this year's work, it is felt that the tritium system and tritium release mechanisms will dominate the low consequence, high probability risk envelope for the hybrid facility. The relative risk potential of the tritium systems in a hybrid reactor should be assessed.

- In considering ways in which radiation can be released to the atmosphere, it was pointed out that the unique feature of the hybrid is the potential for coupled fusion-fission accident events. For example, if a failure in the fission blanket system can lead to a failure in the fusion system, then the consequence is more serious than a separate failure in either system. This area requires further study and evaluation of all possible coupling accidents.
- Analyses should be undertaken to evaluate the effect on structures due to what was termed neutron attenuation anomalies in Section 5.4. A failure of shielding in the fusion reactor could cause unexpected neutron heating of the vacuum vessel or other components and result in a local hot spot. A failure of shielding in the fission blanket could lead to excess power production in the blanket and possible thermal failure of blanket fuel elements.
- A preliminary bounding study examined the aspects of hybrid blanket heating with subsequent radionuclide release to the

containment building atmosphere. Conservative selection of blanket activity release, accident scenario conditions and meteorological dispersion parameters ensure a bounding determination of the hybrid reactor's consequence potential. As a result of this study, the following conclusions are made:

- (1) The tritium dose is negligible by comparison to fission and activation product inventory contributions.
- (2) Activation product radionuclides contribute approximately 25% of the total lung inhalation dose.
- (3) Fission product radionuclides contribute all the thyroid dose commitment.
- (4) The actinide inventory for the uranium blanket dominates the bone dose category. (Plutonium isotopes contribute 95.7% of the reported dose.) Additionally, the bone dose of 290 rem exceeds the 10CFR100 limit by approximately a factor of 2.
- (5) From the standpoint of radiological considerations, specifically bone dose, the thorium hybrid blanket is more attractive than the uranium-blanket counterpart.
- (6) Both blankets were evaluated in a secondary containment structure leaking to the environment at a nominal leak rate of 0.1%/day. This leak rate is representative of a modern LWR lined containment. Since the resultant consequences for either blanket design are close to 10CFR100 limits with the lined design used, it is doubtful if an unlined or more "leaky" containment would be tolerated in the hybrid programs. It is possible that perhaps a double containment option may be necessary if the assumed source term of 1% of the accumulated fuel activities is indeed applicable. In fact, with proper design guidance, mechanisms for this 1% release may not be identifiable for the hybrid reactor.

These observations from the preliminary safety survey completed during FY79 allow an initial assessment of the significant safety aspects of the fusion-fission hybrid reactor concept. They have formed a basis for the recommendations of the hybrid safety program plan. Investigation of hybrid design alternatives to reduce the hazard potential, dose consequences and risk uncertainties identified here comprise the major portion of the initial phase of the proposed hybrid safety program.

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6. HYBRID SAFETY PROGRAM PLAN

The objective of the Hybrid Safety Program is to insure development of an acceptably and demonstrably low public risk for the hybrid concept during its evolution. The Hybrid Safety Program will serve as a framework guiding safety related activities beginning with preconceptual design and continuing through eventual demonstration and commercialization of the now emerging fusion-fission hybrid concepts. A Hybrid Safety Program plan has been developed to accomplish this objective and will now be discussed.

Of necessity, the Hybrid Safety Program plan has been divided into two phases. The first phase, Phase I, defines the safety activities associated with conceptual design, identifies major accident contributors and provides preliminary design option guidance. The second phase, Phase II provides further definition of safety activities as the hybrid design matures into detailed designs. Current safety program emphasis will be placed on Phase I concerns.

6.1 PHASE I - CONCEPTUAL DESIGN PHASE

This phase is broad in scope and its objective is to provide definition, guidance and coordination during the pre-conceptual design phase of the hybrid reactor development program. On the basis of the preliminary hybrid safety survey done during FY79, Phase I will attempt to offer quantitative design guidance so that the safety characteristics of the hybrid concept are enhanced as conceptual designs evolve. The initial step in Phase I will be to consider generic questions that will be applicable to the hybrid concept regardless of the specific fusion driver and other design definition that are used. These questions include:

- What are the comparative safety characteristics of the basic blanket concepts?

The safety aspects of the energy producing, fast-fission fuel and energy producing and fission-suppressed fuel producing blanket concepts must be generically compared in a quantitative manner so that safety considerations can be fully considered in the selection of the desired hybrid reactor operating mode.

- Radioactivity barriers must be investigated for the specific designs and the effect of these barriers on the radioactivity release characteristics and probabilities must be determined. Design optimization of these barriers at the pre-conceptual design stage may allow selection of reactor concepts that have favorable safety features for further development.
- Accident mitigation systems must be considered for the various conceptual designs. These systems may have significant impact on the cost of a hybrid reactor, as they do on that of fission reactors, and the requirements for such systems must be carefully assessed.

Focus of this phase of the program will be to accomplish necessary safety-related definition studies, perform preliminary safety analysis and to offer design guidance input to emerging hybrid concepts.

6.1.1 Definition Studies Task

This task will define the objectives of the overall safety program plan and monitor the conduct of the elements of the plan toward satisfying these objectives.

As part of the definition study task, preliminary hybrid concepts will be examined and possible accident initiators will be identified. These accident initiator sources will be used to delineate significant accident sequences for consideration in the preliminary safety analysis task.

Potential safety concerns will be identified, especially those unique to the hybrid design. Information and analysis tools, as well as data

requirements necessary to analyze these concerns will be identified. The program plan will guide preliminary safety-related fusion-fission hybrid research by defining R&D priorities.

The Hybrid Safety Program Plan will be periodically updated to reflect completion of tasks and the addition of newly defined tasks.

6.1.2 Preliminary Safety Analysis Task

This task will develop and employ systematic methods for the identification, evaluation and cataloging of the main accident-initiating events of a given conceptual hybrid design. Once the initiating events have been isolated, the response of the hybrid design to these initiators will be assessed and event sequences will be constructed. The hybrid's hazardous materials, particularly the radioactive inventories, will be cataloged and effective barriers to prevent their release will be listed. Event sequences sufficient to breach these barriers are of particular interest and will be examined by preliminary risk evaluations.

It is anticipated that event tree representations will be utilized to the fullest extent possible, as they provide the basis for the formulation of the quantitative aspects of risk analysis. Sequence probabilities and uncertainties will be identified for the hybrid event trees. Additionally, preliminary consequences analysis will be performed for the more significant events identified.

The sequence probability estimates along with preliminary consequence analysis results will initially be used to rank the safety importance of events in a preliminary risk evaluation.

6.1.3 Design Guidance Task

This task will provide design guidance in the emerging hybrid reactor design(s). Earlier preliminary safety analysis work on bounding and "typical" accident consideration (Task 6.1.2) will be refined.

Preliminary Probabilistic Risk Assessment (PRA) will be performed on the candidate hybrid designs. The basis for these analyses are the event trees and probability assignments of Task 6.1.2. These risk assessments will then be applied in the systematic comparison of safety related concerns in the hybrid program. Comparisons and recommendations will then be based on a quantifiable risk analysis basis.

The investigation of the important safety issues by the Definition Studies Tasks, followed by Preliminary Safety Analysis Tasks to quantify the safety concerns for these important issues, and leading to quantitative Safety Design Guidance will allow the Hybrid Safety Program to insure that the important issues identified during this initial FY79 Hybrid Safety Study are assessed. Further, as additional safety issues are identified, this plan will provide a logical framework for these issues to be studied and resolved.

6.2 PHASE II - DETAILED DESIGN

Phase II of the safety program begins when preliminary and final design begins on the hybrid reactor. Whereas Phase I of the safety program is meant to deal with the conceptual design phase and is concerned with such issues as identifying the major safety problems and assessing design trade-offs, Phase II of the program is meant to deal with safety issues through the licensing process. Since it is impossible to predict in which way the hybrid reactor program will develop, it is best to outline a long range safety program that will be general and adaptable to changing conditions. The safety program proposed here is believed to suit the needs of the hybrid reactor and is flexible enough to be changed as needed.

The safety program plan for Phase II is divided into eight task areas described below. The tasks are functional in nature but as the program progresses it may be more appropriate to change from functional tasks to ones that are more system and component oriented.

6.2.1 Definition Studies

This is the top level task and is used to lay the foundation for the definition of specific efforts under the remaining tasks and to guide the course of the overall safety program. Safety R&D priorities are defined under this task.

6.2.2 Data Base

The objective of this task is to collect and categorize the data necessary to complete the remaining tasks. There will be considerable reliance on utilizing the growing volume of data accumulated in the operation fission reactors general industry and other related energy industries.

6.2.3 Methods Development

This task develops the calculational models and methods necessary for performing the analytical tasks. Adapting and modifying existing methods from allied industries will be emphasized. However, it is expected that methods development will be necessary for unique coupled fusion-fission accident cases.

6.2.4 Deterministic/Consequence Analysis

The analysis of accident sequences including plant response, release of radioactivity into the environment, dispersion of radioactivity in the atmosphere and health effects will be done under this task.

6.2.5 Probabilistic Analysis

The probabilistic aspects of accident sequences will be evaluated under this task. The various steps include (1) delineating the accident sequences and constructing event trees, (2) calculating probabilities of failure for each event tree branch and (3) evaluating the effects of common cause and human error, and performing parameter uncertainty analyses.

6.2.6 Criteria Development

An important procedure for the design of the hybrid reactor is to identify and specify detailed safety criteria for the plant systems and components. This work will be done under this task.

6.2.7 Testing Program

A major part of the safety program will be the experimental effort to verify safety adequacy and to determine reliability. The effort to define, monitor and evaluate tests will be conducted under this task. Much of the needed safety information can be expected to be obtained under the test programs now underway or proposed such as the Tritium Systems Test Assembly (LASL), Large Coil Program (ORNL), Lithium Spill Experiment (HEDL) and the Engineering Test Facility (expected operation in last decade of 20th century).

6.2.8 Design Review

This task defines the activities for organizing and providing the review of the evolving hybrid design to ensure that necessary modifications to task area work are accomplished.

APPENDIX A
EXAMPLE OF PROBABILISTIC RISK ASSESSMENT (PRA) METHODOLOGY -
THE TRITIUM SYSTEMS TEST ASSEMBLY (TSTA)

This example screening assessment has been undertaken to show how the application of Probabilistic Risk Assessment (PRA) techniques could be utilized in the evolving designs of fusion-based power plants. The Tritium Systems Test Assembly (TSTA) (A.1) was selected as an example system, since a Preliminary Safety Analysis Report (PSAR) has been written and several accident scenarios have already been identified. The approach demonstrated in this brief example assessment is only a preliminary step that is normally taken in developing a more comprehensive risk profile of a conceptual design.

This example is provided in appreciation of the limitations of numerical estimates of the probabilities and consequences of accidents associated with any industry. The set of accidents chosen to represent the TSTA risk profile is taken from the PSAR and is known to be incomplete. However, it does provide a basis upon which additional accidents can be judged. By conservative assessment of those carefully selected and evaluated accidents the results will approximate the true risk profile.

The true risk profile is an idealization. It is a measure of the dose or health effects per plant year of operation, if the number of plants were extremely large. This is obviously incorrect since all the plants are not identical, the number is not infinite and the design will continuously evolve through rectification of design weakness. Thus, the risk profile is a quantitative way to estimate the level of safety in the plant during various stages of design. The alternative to probabilistic risk assessment is engineering judgment at best and just judgment at other times.

For this example coarse screening assessment, the probability values are based on experience data from functionally similar equipment in power

plants and do not reflect the special design conditions of the TSTA (i.e., extreme cold and near vacuum). This gives rise to large uncertainties, a range of at least 30 above and 30 below the median probability estimate. The consequence assessment is based on the models described in the PSAR with the recognition that the uncertainty in those estimates can range at least a factor of 10 above or below the "median" value. This is due to such factors as uncertainty in the source term, extent of the accident damage, and timing of the failures. Hence, there appears to be less uncertainty in the consequence than in the probability assessment.

Even though large uncertainty ranges are associated with coarse screening assessment of (TSTA) accidents, some important design information has been identified. The highest risk elements in the current design are the distillation column and the cryopump even though the overall risk of this design is very low. The highest radiation hazard would cause no acute health effects in the public even though it is possible for accident doses to exceed the site boundary protection guidelines. This is because of the low tritium inventory of less than 200 gms. Recommendations for continued work are presented.

INTRODUCTION

As part of the goal to realize the benefits of fusion power, a test facility is needed to gain the experience necessary to establish future guidelines and requirements for the needed tritium handling systems. The TSTA is dedicated to the development, demonstration, and interfacing of technologies related to the deuterium-tritium fuel cycle for large scale fusion reactor systems. Many of the components and systems have been developed in laboratories and have not yet been integrated into a total system. The objective of the TSTA program is to demonstrate that large quantities of tritium can be handled safely on a routine basis.

The current TSTA safety analysis as described in Ref. A.1 includes four accident scenarios initiated internally by component ruptures or leaks. In addition, accidents initiated externally are discussed. These accident

descriptions were used to develop a coarse screening risk assessment. It must be recognized that this does not represent a fully descriptive set of accident conditions but indicates what some contributors to the risk profile might be. This coarse screening analysis is an example of how PRA is applied and provides a quantitative picture of the accident understanding currently described in the PSAR. No additional systems analysis has been performed.

FACILITY DESCRIPTION

The TSTA process loops and auxiliary systems are shown in the functional diagram of Fig. A.1. The details of its operation are described in Ref. A.1. Some unique features of this system are operation under vacuum in the torus and at very low temperatures requiring liquid nitrogen and liquid helium. Although there are hazards posed by the TSTA operation such as pressure buildup of cryogenic systems during uncontrolled warmup, electrical shorts, mechanical faults, hydrogen fires, explosions from hydrogen-oxygen ignition, and hazards of natural phenomena, the most significant hazard stems from the quantities of tritium handled at the TSTA facility. The total system tritium inventory is about 150 gms and would not exceed 200 gms. Hence, the Curie level inventory range can be calculated as follows:

$$\begin{aligned} \text{Curie level} &= \frac{(0.693 \times 0.602 \times 10^{24})}{A \times t_{1/2} \times 3.7 \times 10^{10}} \times (200 \text{ gms to } 150 \text{ gms}) \\ &= 1.9 \times 10^6 \text{ Ci to } 1.4 \times 10^6 \text{ Ci.} \end{aligned}$$

This inventory is mostly in the gaseous form although some tritium will be in the more biologically hazardous water vapor form as DTO, T₂O and HTO.

The facility consists of the components in the process system housed in a leak tight building. Some of the components have a local secondary containment, but all are contained within the building. In the event of a leakage, an emergency system can be used for tritium cleanup. This is called the emergency tritium cleanup system which removes tritium from the air or water. In the event that this system does not operate, the building acts

Fig. A.1 Functional process diagram with loops and auxiliary systems

as a barrier to release as long as the internal pressure does not increase significantly. If a fire or overpressure condition occurs, then it is assumed that the building is ventilated at the stack. Further details of this mitigation system are described in Ref. A.1.

COARSE RISK PROFILE DEVELOPMENT

Much has been said in the PSAR (Ref. A.1) about accident consequences, furthermore, indications are given of their qualitative probability. However, nothing has been said about constructing a risk profile. Figure A.2 shows some of the key steps in this process. First, work must begin with an understanding of the plant design so that an approximate experience base can be used to select the accident initiating event and define the accident sequences. In this example, the previous level of understanding from the PSAR was used to complete Steps 1 and 2. The consequences of 5 accident sequences were reported in Table 6.1-1 of Ref. A.1 and provided quantitative consequence assessments which were employed in the analysis during Steps 3B, 5 and 5a. Quantification of probabilities in Step 3A was based upon data from Ref. A.2 tempered with additional judgment in areas where experience was lacking such as, cryogenic systems. Thus, these probabilities are only order of magnitude estimates at best.

Figures A.3 through A.6 show the synthesis of probabilities and consequences for each initiating event. Figure A.7 is the coarse screened risk plot that results from risk quantification during Step 6. At this point, it is noted that the two highest risk contributors involve accidents initiated by failures in the distillation column and cryopump. More detailed review of these accident scenarios is therefore suggested by the feedback loop in Fig. A.2. In addition, it is fully recognized that additional accident sequences should be analyzed. The type of accidents not addressed so far are the "transient" events initiated by such failures as faulty valve operation. Failures of this type can induce potential thermal stress problems that significantly increase the rupture likelihood. Delineation of transient accident scenarios requires the development of a data base of experience on similar systems so that previous system interactions under

Fig. A.2 Steps in constructing a probabilistic risk assessment

Fig. A.3 Example event logic tree for ruptures and leaks without secondary containment (Accident No. 1)

Fig. A.4 Example event logic tree for cryopump rupture (Accident No. 2)

Fig. A.5 Example event logic tree for distillation column rupture (Accident No. 3)

Fig. A.6 Example event tree for transfer line rupture (Accident No. 4)

Fig. A.7 Example frequency-consequence plot for the tritium system test assembly (TSTA). Based on information in Ref. A.1 and estimates of generic equipment failure rates.

accident conditions, as part of the consequence assessment, becomes a key element in aiding the designer as conceptual designs move toward hardware.

COARSE SCREENING RISK PROFILE RESULTS

The accidents discussed in Ref. A.1 have been delineated in event trees of Figs. A.3 to A.6. The consequence assessment is based on the calculated dose in mrem at the site boundary as presented in the PSAR (Tables 6.1-1). Probability evaluations are based on review of the FMEAs in Ref. A.1 and the operating experience reported in Ref. A.2. In the interest of space, the preliminary fault trees are not shown. The fault tree details are only taken to the system level identified in Fig. A.1. Thus, the probability estimates are very coarse and do not reflect the details of design. Considerable effort is needed to more precisely define the fault trees and evaluate the probabilities.

The results shown in Fig. A.7 indicate that failures of the distillation column and the cryopump represent the dominant risk contributors for the accidents analyzed thus far. The earthquake point is plotted only because both the probabilities and range of consequences are discussed in the PSAR. The major difference in the earthquake points is due to the weather conditions rather than plant design features. The transfer line rupture and the torus rupture appear to have somewhat less significance in this coarse screening assessment. Hence, additional effort such as expanding the fault trees and event trees and providing a rational basis for the probability evaluations for the distillation column and cryopump failures is the next step needed to aid the design evolution.

RECOMMENDATIONS

Based on the screening assessment results, the following areas of additional work would aid the TSTA design, and later contribute to greater understanding of potential-accident sequences.

1. Refine the reliability data by collecting, storing, and synthesizing applicable experience.
2. Perform a detailed review of the distillation column and cryopump failures.
3. Define and analyze new accident sequences involving fires and valve failures which give rise to system transients and hazardous releases.
4. Quantify uncertainties in both the estimates of probability and consequences. Develop uncertainties in the scenarios modeled.

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