PREFACE

RADIOACTIVATION OF FUSION STRUCTURES

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The following six papers represent a cross section of the invited presentations made in two special sessions at the 1982 Winter Meeting of the American Nuclear Society (ANS) in Washington, D.C., on the subject of "Radioactivation of Fusion Structures." Additional papers from these special sessions are expected to be published in a forthcoming issue of this journal.

Plans for this "minisymposium" originated within the ANS Isotopes and Radiation Division and were carried forward in collaboration with members of the ANS Fusion Energy, Radiation Protection and Shielding, and Materials Science and Technology Divisions. The organization of this event benefited greatly from help by the following individuals: Bernard Engholm and George Hopkins (GA Technologies Inc.), George Miley (University of Illinois), Robert Conn (University of California, Los Angeles), and Everett Bloom (Oak Ridge National Laboratory). As the program for these sessions crystallized, it became apparent that the theme, "Radioactivation of Fusion Structures," might be too narrowly conceived and perhaps should include the coolant-breeder system. This broader viewpoint in fact was adopted in some of the papers.

As for the rationale for the minisymposium, it seemed timely to provide a comprehensive exposition of the radiological hazards expected from the radioactivity buildup in fusion reactors and of available strategies for reducing the risks. In recent years there has been a growing realization in the fusion technology community that the radiological risks associated with fusion power could become significant under some conditions. For example, earlier studies have suggested that the maximum (public health) hazard potential from a tokamak reactor fueled by deuterium-tritium (D-T), with a liquid lithium coolant/breeder and a stainless steel or molybdenum structure, could come close to that of a light water fission reactor. This could create a serious problem for the ultimate public acceptance of fusion power unless viable approaches are available for limiting the buildup of a (long-lived) radioactivity inventory. Second, a panel was convened by the U.S. Department of Energy in early 1982 under the chairmanship of Robert Conn to examine the feasibility and utility of using low-activation materials in fusion reactor designs. It seemed desirable to present to the community a progress report by this panel. Finally, it was hoped that having this issue explored at a regular meeting of the ANS (rather than at one of the periodic fusion topical meetings) would promote a more extensive involvement of additional related disciplines within the ANS (such as reactor safety, waste management, etc.).

The two sessions collectively were organized into three main elements:

1. predictions of induced radioactivity for near-term (D-T) fusion experiments [the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET)] and fusion reactor

conceptual designs [STARFIRE, Fusion Engineering Device/International Tokamak Reactor (FED/INTOR)]

2. safety and waste management considerations
3. the benefits and feasibility of low-activation designs and an assessment of low-activation materials.

The following is a distillation of the main ideas and conclusions that emerged from the various presentations. Radioactivation is already a significant concern in the various upcoming fusion experiments, even though the total (D-T) neutron production will be relatively small [up to 10^{19} for TFTR (Q = 1) and up to 10^{24} for JET]. In these machines, component modification and maintenance are important factors in the operational scenarios. Analytical predictions of induced radioactivity levels show a need for semiremote handling and access control in TFTR. In JET, repair and maintenance will be conducted completely remotely, without breach of the shield wall. Some additional access restrictions to the JET reactor hall are necessary to maintain the radiation dose to individuals below 100 mrem/yr. In conceptual designs for various future power reactors (e.g., STARFIRE, FED/INTOR), the problem of induced radioactivity is receiving considerable attention, including its impact on reactor maintenance, reactor safety, and waste disposal. Minimum goals are proposed for each of these three areas. For waste material management, the minimum goal would be to keep radioactivity levels in waste to below 1 Ci/m^3 (Class C waste, according to the proposed 10CFR61 guidelines). For reactor safety, it would be to assure that a worst-case accident does not produce death or somatic effects. The maintenance objective would be to achieve contact maintenance conditions within 14 days after shutdown (the most stringent requirement). These goals provide a means for classifying candidate materials according to their activation properties, with a parallel classification being in terms of effective decay times. Thus very low activation materials would be those that meet all three goals and equivalently decay by $\sim 10^6$ in <2 weeks (satisfied by carbon, silicon, high-purity aluminum, and magnesium). Low-activation materials meet the safety and waste management goals only, decaying by $\sim 10^6$ in <10 yr (vanadium and titanium). Moderate activation materials would satisfy only the Class C waste goal, with $\sim 10^6$ decay within 100 yr (chromium, iron, zinc, tungsten, and cobalt). The waste management goal generally is achievable by elimination of a few long-lived activity elemental components (nickel, molybdenum, and niobium) and by control of certain impurities (especially nitrogen). An illustration of waste disposal requirements is provided by the STARFIRE reactor conceptual design (water-cooled), which assumes a structure of modified Type 316 austenitic stainless steel—the primary candidate alloy (PCA), with a solid breeder ($LiAlO_2$) and a neutron multiplier (Zr_5Pb_3). The primary concerns are the first wall, blanket, neutron multiplier, and reflector, which contain 99% of the total radioactivity inventory. At shutdown, 95% of the biological hazard potential (BHP) is contained in the Zr_5Pb_3; after 1 yr the BHP is dominated by the PCA. The PCA requires transport in shielded cases (after size reduction by cutting, etc.) and geological storage as high-level waste. Radiation damage products alone result in ~ 60 m^3/yr of waste, primarily from the $LiAlO_2$ and graphite reflector (low-level waste), neutron multiplier, and PCA. Routine maintenance and coolant purification produce a total of 900 m^3/yr of low-level waste (estimated from waste production in pressurized water fission reactors).

The safety goal is complicated by involving a combination of activation characteristics and physical properties such as melting/vaporization temperatures that govern the response to afterheat. Thus, in case of a postshutdown cooling interruption, stainless steel would melt in 2 h, aluminum in 17 min, while no melting would occur for silicon carbide (SiC) and graphite. Approaches to the reduction of hazards (potential irradiation of workers, and of the public through radioactivity release) should be evaluated in terms of effectiveness versus cost. (This cost may include a delay in the commercialization of fusion power.) The largest hazard reduction available comes from combining low-activation materials with low-stored-energy coolant/breeder systems. The penalty may be larger tritium inventories; also, in reducing short-lived radioactivity inventory to lessen the accident release hazard, care must be taken not to aggravate the waste problem. In terms of actual reactor materials, the achievement of the contact maintenance goal is possible only with graphite, SiC, and ultrapure aluminum and Al-Si-Mg alloys. All components in the high-radiation field would have to be made out of such materials, although this probably is not feasible. Thus as limiter or divertor materials, graphite and aluminum suffer from high erosion rates; SiC and carbon are brittle organic materials that are difficult to engineer into structural components, and aluminum has a low melting point. A general problem is an inadequate data base on radiation damage. In terms of a general reduction in the radioactivity inventory, the most attractive candidates are vanadium alloys. In addition to good high-temperature strength, combined with good radiation resistance and compatibility with liquid lithium, they offer specific safety advantages including a high melting point and low afterheat. A major disadvantage is their reactivity to oxygen with strong negative effects on ductility. Austenitic steels can be given significant improvements in activation properties by removing molybdenum, and further by removing

nickel. Thus the activity of an Fe-Mn-Cr austenitic drops below that of SiC (1 appm iron) in 30 yr. High purity, especially with regard to nitrogen and niobium, is essential to acceptable activation performance. The isotopic tailoring of alloys to remove troublesome isotopes of essential or valuable constituents is not viewed as a credible option; it does not appear economically reasonable and may be difficult to develop on the time scale of interest.

While in the collection of papers published here the problem of induced radioactivity is discussed mainly in the context of toroidal confinement systems, it is obvious that the considerations presented apply to any fusion system producing energetic neutrons. This specifically includes mirror reactors, and also inertial confinement systems. It is hoped that these papers will stimulate further progress in dealing with radioactivation and its consequences for the safety, economics, and public perception of fusion power.

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