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POTENTIAL FOR GRAPHITE USE ADJACENT TO
THE PLASMA IN NUCLEAR FUSION REACTORS

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ABSTRACT

The need to reduce high Z impurities in the plasma of fusion reactors has led to various ideas, including a low-Z liner, for isolating the first structural wall from the plasma. Graphite and other carbon containing materials (most notably SiC) are strong candidate materials for such liners. However, to assess the potential of these materials will require more information on the following properties:

- Radiation effects under fusion reactor environment
- Sputtering
- Degassing.

This document describes the current state of knowledge on carbons and graphites in each of these areas.

Radiation data on graphite are readily available for samples irradiated in fission reactor spectra up to temperatures of about 1400°C. The present application, however, requires an assessment of radiation behavior to temperatures up to 2000°C and at fluences at least up to $4 \times 10^{22} \text{ cm}^{-2}$ EFF. Extrapolation of current data to higher temperatures is impossible due to the complicated nature of radiation damage in graphite. Studies currently under way to correlate fusion reactor radiation effects with those measured in fission reactors are described.

No data on neutron sputtering of graphite exist and, while experimental confirmation is required, it is felt that this mechanism will not be limiting. However, physical sputtering by energetic ions or atoms and chemical sputtering (i.e., chemical reactions) by excited hydrogen species is of substantial concern. Work on these areas is currently underway at various laboratories and preliminary results are reviewed.

Degassing behavior of graphites has been investigated for small samples, but data from larger samples are needed. Existing data are reviewed and a program initiated to obtain additional data is described.

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1.0 INTRODUCTION

Although it has not been definitely proven, there seems to be fairly general consensus that the transfer of high-Z species from the first wall of fusion reactors into the plasma must somehow be minimized. There is less agreement, however, on schemes for achieving this objective, but the following are among those considered: diverters, gas blankets, low-Z coatings on the first wall, separate low-Z liners, honeycomb or other geometric patterns, or possibly combinations of two or more of these methods. Conceptual power reactor studies during the past couple of years have placed increasing emphasis on graphite coatings or liners. These studies have pointed out areas where the necessary property data are insufficient or nonexistent for such applications, most notably as follows:

1. Correlation of radiation-damage effects between fission and fusion reactor spectra.
2. Radiation effects on carbon and graphite cloth.
3. Degassing.
4. Very high temperature radiation effects on graphite in general.
5. Neutron, ion, and chemical sputtering.

More recently, the first results of three conceptual design studies have been published⁽¹⁻⁵⁾ for an Experimental Power Reactor (EPR) which is currently scheduled⁽⁶⁾ for the beginning of Title I design in 1978 and construction completion in 1986. Graphite, along with other materials, is being considered for use inside the vacuum wall of this machine, but these preliminary studies emphasize the need for more property data (particularly items 3, 4, and 5 above) to determine the suitability of candidate materials for the intended applications.

All of the schemes suggested above for reducing high-Z plasma impurities were discussed in the three EPR design studies, but most attention was devoted to liners or coatings using graphite or silicon carbide. Other materials mentioned for possible use as liners or coatings, although with less consistency among the three studies, included various carbides, oxides, nitrides, and even refractory metals such as W and Nb. In addition to a liner, the General Atomic (GA) EPR design calls for the use of plasma limiters in the form of graphite projections placed on selected liner plates. The final decision on the suitability of these materials must await data on radiation effects, sputtering (particularly chemical sputtering in the case of graphite), and degassing. Knowledge of other materials properties are also needed, but data on these three properties appear to be most critical for choosing the liner or coating material and even for evaluating the relative merits of liners or coatings compared to other possible techniques for limiting plasma impurities.

Despite the uncertainties, each laboratory has chosen, for detailed analyses, a reference EPR design that includes graphite or silicon carbide as a coating or liner under the conditions shown in Table I. Notably, the calculated graphite liner temperatures (1700-1800°C) are well above the range of existing radiation data on graphite.

In addition to their EPR design studies, GA has made an extensive study^(7,8) of the use of low-Z materials for minimizing high-Z plasma impurities. They have ranked a variety of possible materials for various applications such as liners, coatings, etc., and concluded, on the basis of thermal and mechanical properties, that C and SiC are most suitable. They also pointed out a number of other advantages of these two materials not the least of which is the large amount of existing radiation data and their extensive use in fission reactor applications.

TABLE I. SELECTED REFERENCE EPR PARAMETERS

Design Laboratory	Neutron Wall Loading, MW/m ²	Liner or Coating		
		Material	Thickness, mm	Maximum Temperature, °C
ANL	~0.2	C or SiC coating	1-4	~600
ORNL	0.4	Graphite liner*	3	1779
GA	1.36	Graphite liner	5	~1700

*ORNL appears to have initially adopted the use of a graphite liner in their reference design, but then backed away from being so specific prior to publication of their results.

Experimental programs are currently in progress or planned at PNL to supplement the limited information available in the five areas where graphite data are most needed. Brief descriptions of programs currently underway in areas 1 to 3 together with brief literature reviews of these areas are presented here. As a prelude to planned experiments in areas 4 and 5, the literature on chemical sputtering and on high temperature radiation effects in graphite is reviewed.

Chemical sputtering is a result of chemical reactions of carbon with hydrogen species present in the plasma. To date, the literature on chemical sputtering *per se* is very limited. However, several studies have been conducted on reactions of carbon with molecular hydrogen and hydrogen atoms, and to a much lesser extent with ionic hydrogen species. Since all of these species may be involved in the chemical sputtering process, a brief review of each is included.

Radiation effects data on graphite, on the other hand, are very extensive for temperatures up to $\sim 1200^{\circ}\text{C}$ with some data extending to $\sim 1500^{\circ}\text{C}$. Engle and Eatherly have reviewed these data through 1971.⁽⁹⁾ The present review, therefore, only very briefly covers the lower temperature data as a lead-up to more recent data in the 1200-1500 $^{\circ}\text{C}$ range. The latter are then discussed with regard to what might be inferred about graphite behavior at even higher temperatures where no data currently exist.

2.0 GRAPHITE RADIATION DAMAGE

The extensive radiation data on carbons and graphites have been obtained through fission reactor irradiations. Much of these data will be useful for projecting graphite performance in fusion reactor applications providing that the effects of the different neutron spectra can be correlated with sufficient confidence. Most, if not all, of the additional radiation data required for fusion applications (viz., data at very high temperatures to ~2000°C and on graphite cloth over the whole range of applicable temperatures) must also come from fission reactor irradiations at least until a high-volume, high-flux 14 MeV neutron source becomes available.

The question is sometimes asked why ion bombardment, which is often used to simulate neutron radiation damage in metals, cannot be used to simulate damage in graphite. The fact is that such a technique would simply not work for graphite because all property changes of interest for fusion applications are bulk effects. That is, they are the result of interactions between crystallites and between grains rather than simply being some average of what happens within individual crystallites and grains. Furthermore, damage within individual crystallites is a function of crystallite size and perfection, both of which vary widely from one type of graphite to another and even within a single graphite. This even further complicates the problem. Thus, the minimum size of specimens used for determination of radiation damage effects must be several times the grain size which usually means they must be at least 3 mm and preferably larger. Since ion penetration depths are far short of this value, ion bombardment is not a useful technique for simulating neutron radiation damage in graphite. A possible exception may be carbon fibers which are typically 6 to 10 μm in diameter.

One is left, therefore, with the task of properly correlating the relative radiation damage effects between fission and fusion reactors. This is likely to be a far easier task than is the case for metals because, as discussed later, helium produced in graphite via n- α reactions apparently will simply diffuse out. Thus, the correlation involves simply the determination of the relative number of atomic displacements in the different spectra. The following paragraphs discuss the correlation of damage in fusion reactors with that in fission reactors, irradiation stability of graphite and carbon cloths, and graphite irradiations at temperatures up to 2000°C.

2.1 FISSION-FUSION CORRELATION OF RADIATION-DAMAGE EFFECTS

Correlations of the relative radiation-damage produced in graphite per unit neutron fluence in different reactor spectra are currently based on calculations^(10,11) of atomic displacement rates, which can be defined as

$$\dot{D} = \sum_{i=1}^{\infty} \sigma_d(\Delta U)_i \phi(\Delta U)_i$$

where $\dot{D}$ = the number of atomic displacements per atom per unit time

$\sigma_d(\Delta U)_i$ = the atomic displacement cross section for the i^{th} lethargy group of width ΔU

$\phi(\Delta U)_i$ = the neutron flux intensity for that lethargy group.

In calculating^(10,11) the atomic displacement cross sections, $\sigma_d(\Delta U)_i$, some simplifying assumptions were made such as ignoring the high-energy reactions, n- α , n-p, and n-2n, etc., which may be important contributions in fusion reactor applications. However, the effects of these and other simplifications tend to cancel; thus, the derived atomic displacement cross sections should provide a reasonable approximation to the relative damage production rates.

There are, however, enough uncertainties to warrant experimental confirmation of the relative number of displacements as a function of neutron energy. Such an experiment is currently in progress at PNL to confirm, or adjust, the calculated atomic displacement cross sections. Samples of stress-annealed pyrolytic graphite are being irradiated in different neutron source facilities (e.g., the RTNS at LLL, the D-Be source at Davis, California, and the Hanford N-Reactor), and the relative radiation damage (i.e., the relative number of displaced atoms) in the different neutron spectra is being measured. Factors omitted from the calculations, such as the $n-\alpha$ reactions, will automatically be included in the experimental determination.

While displacements resulting from $n-\alpha$ reactions will be accounted for by the experiment described above, there remains the question of whether the helium will be retained in graphite and, if so, what its effect will be. Two recent experiments indicate that the helium will not be retained at elevated temperatures.

Bauer et al.⁽¹²⁾ bombarded graphite with 300 keV He and measured the fraction of He re-emitted. A conventional polycrystalline graphite re-emitted nearly 100% of the He at 400°C. Higher temperatures (800-1200°C) were required before He release approached 100% from a well-oriented pyrolytic graphite. These experiments, however, also produced some surface damage in the graphite which leaves one to wonder whether the He would have been released as readily in the absence of surface damage.

Holt et al.⁽¹³⁾ irradiated polycrystalline and well-oriented pyrolytic graphite in the 15 MeV neutron beam of the RTNS at LLL. Helium release from these samples was then measured as a function of temperature. All of the helium was released from the polycrystalline graphite by 700°C and from the pyrolytic graphite by ~1300°C.

These two types of experiments are thus in approximate agreement although it is not clear how well they agree in detail regarding time and temperature dependencies of the helium release. At any rate, it would appear that helium generated via n- α reactions should present no problem for graphite operating at elevated temperatures. On the other hand, carbon coatings deposited on the first structural wall of fusion reactors have been proposed. Coatings would operate at much lower temperatures than separate graphite liners and may not, therefore, release all of the helium. This possibility together with any effects due to retained helium merits investigation.

2.2 RADIATION EFFECTS ON CARBON AND GRAPHITE CLOTH

Neutron irradiation data on carbon and graphite fibers are very limited. A few papers (e.g., references 14-18) deal with structural and mechanical property changes at maximum fluences up to $\sim 1 \times 10^{21} \text{ cm}^{-2}$ EFF.* We are aware of only one paper⁽¹⁹⁾ where dimensional changes of irradiated fibers are reported. Of three types of fibers irradiated, the extreme case was for Thornel 50S whose diameter increased about 50% after irradiation to $1.6 \times 10^{21} \text{ cm}^{-2}$ EFF at 400-700°C.

Recent preliminary results at PNL⁽²⁰⁾ have been obtained for cloth and fibers irradiated at $\sim 500^\circ\text{C}$ to $\sim 3 \times 10^{21} \text{ cm}^{-2}$ EFF. All four types of thin cloth samples irradiated remained intact but the fibers in each case shrank about 8% in the axial direction. Diameter measurements on other types of fibers also showed shrinkages of up to about 10%. The only exception was Thornel 50S which expanded slightly in contrast to the $\sim 50\%$ expansion reported by Peggs⁽¹⁹⁾ at a lower fluence. These two results are not necessarily in disagreement since the material may expand initially

*All fluences are quoted in terms of "Equivalent Fission Fluence for Damage in Graphite."⁽²¹⁾ A fluence of $1.52 \times 10^{21} \text{ cm}^{-2}$ EFF produces one displacement per atom (dpa) in graphite.⁽¹⁰⁾

and then shrink. Additional data on cloths and fibers irradiated at $\sim 500^{\circ}\text{C}$ to ~ 6 and $\sim 9 \times 10^{21} \text{cm}^{-2}$ EFF will be reported from our Laboratory about September 1976.

Although fiber shrinkages observed at PNL are large compared to those found in conventional polycrystalline graphites, the use of graphite cloth in fusion reactors is not necessarily precluded as long as the cloth remains intact. Additional data at higher temperatures and fluences will be required before the suitability of graphite cloth for such applications can be determined.

2.3 REVIEW OF HIGH TEMPERATURE, HIGH FLUENCE DIMENSIONAL BEHAVIOR OF GRAPHITE

The radiation-induced dimensional changes in graphites are highly dependent on morphology and are the net result of several competing processes; ⁽²²⁻²⁵⁾ thus, there is a wide range of differences in behavior for the various types of graphites. This "individuality" of behavior becomes increasingly apparent as the irradiation temperatures are increased and as the fluence increases beyond that of maximum volumetric contraction. Nevertheless, some generalizations can be made if we limit the discussion to "conventionally processed nuclear graphites" ⁽²⁵⁾ and remember that moderate differences in behavior exist even within this class of materials.

The pioneering investigations at high temperatures by Helm and others ⁽²⁶⁻²⁹⁾ showed that as irradiation temperatures increased above about 450°C , both the rate of contraction in the transverse direction and the maximum volumetric contraction decreased to minimum values somewhere around $700-900^{\circ}\text{C}$. At higher temperatures, nominally in the range $900-1100^{\circ}\text{C}$, contraction rates in the transverse direction increased rapidly with temperature, the maximum volumetric contraction also

increased, and rapid volumetric expansion began at much lower fluences than at the lower temperatures. At still higher temperatures, the initial contraction rate in the transverse direction continued to increase with temperature, but volumetric expansion at high fluence was observed to occur at a much lower rate.⁽³⁰⁾ Figure 1, which shows the transverse length changes for an extruded Gilsocoke graphite, 65-22,⁽³¹⁾ illustrates the general behavior for temperatures above 1000°C.

In contrast to the instrumented irradiation capsules used by Helm and others⁽²⁶⁻³¹⁾ to obtain data at controlled and closely spaced temperature intervals, much of the early irradiation data for the Dragon Project was obtained from noninstrumented irradiations in fuel splines of the Dragon Reactor where temperatures vary during the irradiation period.⁽³²⁾ These data were supplemented by data at 600°, 900°, and 1200°C from controlled temperature irradiations in the HFR at Petten.^(32,33)

Figure 2 shows a typical plot of fluence and time-average temperature for an irradiation in the Dragon Reactor, and Figure 3 shows data for samples of a graphite irradiated in the spline. Because of the variations in temperatures during the Dragon Reactor irradiations, the simplified assumption that the contraction rate increases progressively with increasing temperature above 900°C has often been used. The analyses prior to that of Van den Berg et al.⁽³⁴⁾ were, in fact, based on this *a priori* assumption; Figure 4 illustrates the isodose curves which result from such an analysis.

The sole reason^(34,35) for the paper of Van den Berg et al. was to point out that previous analyses of the Dragon Reactor data were in error and that the behavior of graphite is a much more complex function of irradiation temperature than had been assumed by some analysts. The isodose curves, such as those shown in Figure 5, that were used as illustrations by Van den Berg et al. appear to indicate that three graphites reach their

FIGURE 1. Transverse Length Change as a Function of Fluence and Temperature for an Extruded Gilsocoke Graphite.

FIGURE 2. Typical Axial Neutron Fluence and Temperature Distribution for Dragon Reactor Irradiations.

FIGURE 3. Dimensional Changes of G5 Graphite Versus Height In Dragon Reactor Core.

FIGURE 4. Isodose Dimensional Changes in the Axial Direction of a Molded Petroleum Coke Graphite.

FIGURE 5. Isodose Dimensional Changes in the Axial Direction of a Molded Petroleum Coke Graphite.

maximum volumetric contraction at a lower fluence and begin to expand more rapidly when irradiated at 1350-1400°C than when irradiated at 1100-1200°C. [However, the expansion does not appear to be as rapid as for the 900-1100°C irradiation temperatures.]^(34,35) Although this feature of the isodose curves was not remarked upon by Van den Berg et al., others⁽³⁾ appear to have reached the unfounded conclusions that: (1) it is a universal characteristic for all graphites, and (2) it indicates a trend which will continue with further increases in temperature.

In regard to the first conclusion, that it is a universal characteristic, it should be noted that:

1. These three graphites were selected to illustrate the complexity of the isodose curves, not because they are typical of graphites considered as candidates for high-temperature applications.
2. Data on other graphites^(31,36) irradiated to higher fluences than those shown have not exhibited this "cross-over" in expansion. Figures 1, 6, and 7 are examples of graphites which have not exhibited this behavior.

In regard to the second assumption, it should especially be noted that the purpose of the paper by Van den Berg et al. was to correct the errors introduced because of a similar *a priori* assumption.

In addition, it should be noted that the irradiation data presented by Van den Berg et al. appear to have been compiled from at least three separate series of irradiation capsules.^(34,37) Correlations of data from different irradiation facilities can be rather difficult; although uncertainties in the correlations are thought to be much too small to alter the general conclusions of Van den Berg et al., they could have a more critical effect on the 1100-1200°C versus 1350-1400°C comparisons.

In summary, the dimensional behavior of a grade of graphite cannot be reliably predicted from data on another grade of

FIGURE 6. Dimensional Changes of a Molded Pitch Coke Graphite.

FIGURE 7. Transverse Length Change as a Function of Fluence and Temperature for an Extruded Petroleum-coke Graphite.

graphite; nor can data be reliably interpolated or extrapolated for large changes in temperature or fluence. Additional graphite irradiations need to be performed for CTR design purposes as follows:

- Although graphites such as those in Figures 1, 6 and 7 have not shown the type of "cross-over" behavior represented by Figure 5, additional data are needed to determine if these or other graphites exhibit the "cross-over" behavior at higher fluences.
- Data are needed at intermediate and higher temperatures (up to 2000°C) to determine how different graphites behave at these temperatures.
- After the data are compiled, a critical analysis needs to be undertaken to determine the impact of graphite dimensional changes on reactor component design.

3.0 CHEMICAL SPUTTERING

Material can be removed from the first wall of fusion reactors by neutron sputtering, physical sputtering (from ions or atoms), or chemical sputtering (chemical reactions). Although no measurements are currently available on neutron sputtering of graphite, it has been assumed⁽³⁸⁾ that the yield from this mechanism will be substantially below that from physical or chemical sputtering. In recent months, several papers have reported the results of measurements of carbon removal by hydrogen atoms at thermal energies^(39,45) or by hydrogen ions at energies in the keV range.^(46,52) A third type of experiment has also been reported,⁽⁵³⁾ which uses a mixture of energetic atoms and ions.

3.1 HYDROGEN ATOM-CARBON REACTIONS

Early work on the reaction of graphite with atomic hydrogen was briefly reviewed previously.⁽³⁹⁾ In summary, these experiments were primarily conducted at and below room temperature and yielded methane as the principle product. The reaction

rate was reported to be one-half order with respect to hydrogen atom concentration with an activation energy of 7-9 kcal/mole.* Hydrogen atom recombination occurred on the graphite surface at a rate several orders of magnitude faster than the rate of methane formation with an activation energy of only 2 kcal/mole.⁽⁴⁰⁾ A low rate of methane formation relative to hydrogen atom recombination was also reported by Vastola et al.,⁽⁴¹⁾ who generated atomic hydrogen by microwave discharge. Gil and co-workers⁽⁴²⁾ reported that hydrogen generated on a hot tungsten filament reacts with various carbon forms at 77°K producing methane and significant quantities of alkanes with up to four carbon atoms per molecule and also a measurable quantity of an unidentified condensed hydrocarbon.

In the study by Wood and Wise⁽³⁹⁾ hydrogen atoms, generated by a radiofrequency electric discharge, were reacted with graphite to yield methane as the primary product (91%); the remaining 9% consisted of hydrocarbons in the range from C₃ to C₈. The rate was one-half order with respect to hydrogen atom concentration, but also appeared to have a first order dependency upon the molecular hydrogen (H₂) concentration. In the range from 455 to 715°K, the rate increased with temperature with an apparent activation energy of 5.6 kcal/mole. At higher temperatures, the reaction rate decreased with increasing temperature becoming immeasurably slow at 1200°K. Recently Gould⁽⁴³⁾ observed a similar temperature dependence for methane production using hydrogen atoms produced on a hot tungsten filament. The rates were measured in the temperature range from 400 to 1200°K with the maximum rate occurring at about 700°K. Hydrogen atom adsorption and desorption rates were also measured. The suggested mechanism for the reaction involves a hydrogen atom contacting an associated pair of chemisorbed hydrogen atoms to form an adsorbed CH₃ group. Methane is then produced by rapid addition of another adsorbed H followed by desorption of the methane molecule. The

observed decrease in methane formation rate with time is explained by a mechanism where the adsorbed CH_3 group may react with an adjacent CH_3 group to form a stable species which blocks further CH_4 production at that site.

Recent measurements by Balooch and Olander⁽⁴⁴⁾ on the reaction of thermal H atoms formed by thermal dissociation of H_2 on a tungsten filament show somewhat different results. Methane formation rates were observed to be reasonably constant from 400 to 600°K. Above 600°K the rate of CH_4 formation decreased and at 800°K was immeasurably small. At 1000°K, acetylene began to form at a rate which increased with increasing temperature up to 2000°K, the maximum temperature examined. The selectivity of H atoms for crystalline direction in graphite was demonstrated by comparing the rate of reaction of the basal plane surface of well oriented pyrolytic graphite with that of the prism or edge plane surface. The attack at the prism plane exceeded that of the basal plane by about a factor of four at all temperatures.

The selectivity of H atom attack on graphite has also been observed by Veprek and co-workers.⁽⁴⁵⁾ They reported an anisotropic attack on carbon fibers and predicted that the reaction probability will be significantly enhanced by high-energy-particle radiation damage to the carbon surface.

In summary, several groups have investigated the reaction of carbon with H atoms but further work appears to be required under carefully controlled conditions before a unified understanding of the reaction will emerge. Particular emphasis should be placed on the reaction at target temperatures in the range of 1000 to 2500°K and on the effect of the carbon structure on the reaction rate. The recombination of H atoms on the carbon sample appears to be well established. However, in our opinion, evidence must be obtained that the hydrogen actually arises from the recombination of atoms rather than from decomposition of CH_4 . The latter mechanism may lead to a substantial degradation of the graphite surface which would not be detected in studies where the rate is followed only by product yield.

3.2 HYDROGEN ION-CARBON REACTIONS

Although several groups have reported results on sputtering of a variety of metals by hydrogen ion bombardment, similar studies on carbon materials are just beginning. Early results from Dr. Gusev's laboratory in the USSR⁽⁴⁶⁾ show sputtering by 10 to 20 keV protons on polycrystalline graphite, pyrolytic graphite, and vitreous carbon. They reported maximum sputtering yields of about 0.085 atoms/ion. The rate of carbon removal was determined by weight loss measurements on a sample bombarded by a 300 microamp/cm² proton beam. The sputtering yield did not appear to depend upon the carbon structure, but the high yield was nevertheless attributed to a chemical reaction yielding volatile hydrocarbon compounds. Later results from the same laboratory⁽⁴⁷⁾ using a comparable ion beam showed an effect of temperature on the sputtering yield; in the temperature range from about 700 to 1000°K, a sputtering yield of 0.085 atoms/ion was reported. Above 1000°K, the yield decreased and at about 1400°K leveled off at a value of about 0.03 atoms/ion. The high sputtering yield was attributed to chemical reactions with the formation of CH₄ and the lower yield at high temperatures was considered to be the result of purely physical sputtering. At about the same time, similar results were also reported by Behrisch and co-workers.⁽⁴⁸⁾ Smith et al.⁽⁴⁹⁾ used Auger electron spectroscopy to investigate carbon sputtering by 11 keV protons at ambient temperature by measuring the removal rate of thin films. For pyrolytic graphite, they observed a sputtering yield of 0.011 atoms/ion, well below that reported by other workers. Roth et al.⁽⁵⁰⁾ reported sputtering yields of pyrolytic graphite by 300 to 6000 eV hydrogen ions in the temperature range from 400 to 1000°K. The sputtering yield was observed to increase with temperature to a maximum at about 900°K and the ratio of the maximum yield to that at room temperature was strongly affected by ion energy. In this work, the sputtering yield was reported to also be dependent on carbon structure. Researchers

from the UKAEA Culham Laboratory⁽⁵¹⁾ have also investigated sputtering from carbon with hydrogen ions. They reported that the ions were implanted in the target and then diffused to the surface where the chemical reaction to form CH_4 occurred. The rate of CH_4 formation increased slowly with time until the graphite target became saturated with hydrogen and the saturation value of the CH_4 formation rate was temperature dependent, having a maximum sputtering yield of about 0.08 atoms/ion at 850°K. When the bombardment was stopped, production of methane ceased if the temperature was below 800°K but above that temperature, the reaction continued until the trapped hydrogen was depleted. With the ion beam off, the peak in CH_4 production rate was reported to occur at 1000°K and the hydrogen release rate was a maximum at 1200°K.

A team from the Argonne National Laboratory⁽⁵²⁾ has investigated changes in the surface of a carbon target during ion bombardment with 10 to 15 keV protons and deuterons using Raman scattering. They observed a formation of an amorphous layer on the surface of the carbon. Annealing at a temperature of only 1325°K produced microcrystallites in sizes somewhat smaller than on the original samples. Evidence of $-\text{C}\equiv\text{C}-$ structures formed on the surface was observed but no evidence of C-H or C-D was found. The authors gave no indication as to the sensitivity of such measurements, however.

Some experiments have been conducted using a plasma containing a mixture of energetic ions and atoms. While this plasma may be more representative of fusion reactor conditions near the first wall, the results are more difficult to interpret. The most recent such study was conducted at the University of Wisconsin.⁽⁵³⁾ In this work, bulk carbon samples and graphite cloth were bombarded by a plasma from a Hall source⁽⁵⁴⁾ which produces a pulsed beam of energetic ions and atoms. The sputtering yields were inferred by measuring the step height on samples at the interface between a bombarded area and an area masked

from the beam by a tungsten wire. Maximum sputtering yields of about 0.08 atom/incident particle were measured for the bulk samples at a surface temperature of about 700°K. The graphite cloth samples, however, were reported to sputter at much greater rates with a sputtering yield of 0.23. The calculated surface temperatures of these samples were reported to be 3300°K. At these temperatures reactions to form acetylene and carbon sublimation would appear to contribute significantly to this reaction.

Correlation of the various rather preliminary experiments described is a difficult task. It is clear that methane is formed at temperatures below 1000°K, but the rate of formation as a function of temperature varies from one study to another. This variability in the temperature effects is not yet clearly understood. Energetic ions are implanted in the surface of the target and then apparently diffuse to the surface of the sample where they can react to form hydrocarbons or recombine and be released as H₂. With this mechanism, it would appear that the reaction parameters may be essentially the same as those when thermal atoms react with graphite. Yet there are major apparent differences in products and kinetic parameters. Gusev⁽⁵⁵⁾ has suggested that differences in the low temperature sputtering rate of carbon by hydrogen may be due to differences in ion current density thus giving rise to differences in activated decomposition of adsorbed CH₃ or CH₄. Reaction conditions in the experiments to date are not well defined. Clearly, the recent work is an important contribution to gaining an understanding of the surface chemistry of graphite first walls in fusion reactors, but more thorough studies are needed. High temperature data are particularly important. Also, experiments need to be conducted under ultra high vacuum conditions so that better control of experimental conditions can be achieved. In addition, careful attention must be given to structural effects and changes induced by neutron irradiation. As data from such experiments become available, a reliable assessment of the potential of carbon materials for fusion reactor first walls will be possible.

4.0 DEGASSING

The available literature on graphite degassing properties has been reviewed by Kulcinski et al.⁽³⁸⁾ In general, most gases adsorb only weakly on many types of graphite and, as a result, degassing is much less severe than is commonly thought. For example, Beitel⁽⁵⁶⁾ has shown that the gas evolution from graphites that have undergone a previous 24 hour, 300°C degassing treatment is about the same as from a tungsten filament on a per-unit-mass basis. However, the degassing of graphite is a rather complex problem. Most of the studies to date have been done at pressures greater than 10^{-3} Torr where the remainder of the pumpdown is unknown, or with small (minimum dimension <3mm) samples. In the latter case, the ease with which the graphite was degassed may be optimistic because the diffusion effects which would be present in large pieces are minimized. Finally, the initial degassing of graphite should be done at a temperature that permits water desorption but is low enough to prevent water decomposition reactions because oxygen thus produced can be very difficult to remove.

To supplement the available graphite degassing data, an experimental program is currently in progress at PNL wherein large (minimum dimension at least 10 cm) samples are being tested to pressures as low as 10^{-5} Torr and hopefully lower. Results from this study will enable quantitative determination of outgassing rates in a fusion reactor.

5.0 CONCLUSIONS

- All three EPR design groups consider graphite along with other materials for first wall protection, but emphasize the need for information on radiation damage, sputtering, and degassing before a choice can be made.
- The correlation of radiation-damage effects between fission and fusion reactors is currently based on calculations of the relative atomic displacement rates, and an experiment in progress will permit confirmation or adjustment of the calculations.
- Recent results indicate that the radiation-induced shrinkage of graphite cloth will be large. However, if the cloth remains intact, it may still be possible to use this material in fusion reactors. Data at higher temperatures and fluences are required before the suitability of graphite cloth can be determined.
- Based on the data of Van den Berg et al., an assumption apparently has been made that the dimensional changes of all graphites become increasing severe with increasing temperature above $\sim 1200^{\circ}\text{C}$. Such an assumption is not supported by data on other graphites nor can trends be extrapolated beyond the range of existing data ($\sim 1400^{\circ}\text{C}$).
- The sputtering of carbon by hydrogen is a combination of chemical reactions and physical sputtering with the rate peaking in the temperature range from $400\text{--}1000^{\circ}\text{K}$, the primary chemical product being methane. One author has reported that the sputtering rate with hydrogen atoms increases again above 1000°K producing acetylene. Future work at temperatures up to 2200°K as a function of carbon structure are needed to evaluate the potential of graphite for use near the plasma of fusion reactors.

- Available data indicate that graphite degassing is much less severe than is commonly thought. Data on larger specimens and to lower pressures are required to confirm these findings for fusion reactor applications.

6.0 REFERENCES

1. W. A. Stacey, Jr., Tokamak Experimental Power Reactor Studies, ANL/CTR-75-2 *June 1975).
2. P. N. Haubenreich, Tokamak Experimental Power Reactor: Basic Considerations and Initiation of Studies at Oak Ridge, ORNL-TM-4853 (April 1975).
3. M. Roberts and E. S. Bettis, Oak Ridge Tokamak Experimental Power Reactor Study Reference Design, ORNL-TM-5042 (November 1975).
4. C. C. Baker et al., Review of the General Atomic Experimental Fusion Power Reactor Initial Conceptual Design, GA-A13694 (October 1975).
5. T. Ohkawa, Experimental Power Reactor Conceptual Design Study, EPRI 323 Key Phase Report, GA-A13534 (September 1975).
6. Fusion Systems Engineering Program Plan, ERDA CTR (December 1975).
7. C. Baker et al., Fusion Reactor Design Studies, GA-A13430 (April 1975).
8. L. H. Rovner and G. R. Hopkins, Ceramic Materials for Fusion, GA-A13729 (November 1975).
9. G. B. Engle and W. P. Eatherly, "Irradiation Behavior of Graphite at High Temperature," High Temperature-High Pressure, 4, 119 (1972).
10. W. C. Morgan, "Neutron Fluence and Atomic Displacement Rates For Graphite Irradiations," Nucl. Tech., 21, 50 (1974).
11. W. C. Morgan, "Atomic Displacement Cross Sections for Carbon from ENDF/B-III Data," J. Nucl. Matls., 51, 209 (1974).
12. W. Bauer, G. J. Thomas, and B. Granoff, "Helium and Hydrogen Implantation Effects in Graphite," ANS Trans., 22, 30 (1975).
13. J. B. Holt, D. W. Hosmer, M. Guinan, R. Condit, and R. Borg, "Helium Generation and Diffusion in Graphite," submitted for presentation at the Technology of Controlled Nuclear Fusion, Sept. 21-23, 1976, Richland, Washington.
14. I. D. Peggs and R. W. Mills, "The Effect of Fast Neutron Irradiation on the Structure of Carbon and Graphite Fibers," Tenth Biennial Conference on Carbon, Summary of Papers, June 27-July 2, 1971, pp. 188-189.

15. B. F. Jones, "The Effect of Fast Neutron Irradiation on the Mechanical Properties of Carbon and Graphite Fibers," *Ibid.*, pp. 190-191.
16. B. F. Jones and I. D. Peggs, "The Effect of Fast Neutron Irradiation on the Structure and Mechanical Properties of a High Modulus Graphite Fiber," J. Nucl. Matls., 40, 141 (1971).
17. R. E. Bullock, "The Effects of Fast-Neutron Irradiation on Tensile Strengths of Carbon Fibers," Rad. Effects, 11, 107 (1971).
18. B. J. Wicks, "The Effect of Neutron Irradiation on the Structure and Mechanical Properties of Carbon Fibers," ARL/Met., 93 (1974)
19. I. D. Peggs, "Changes in Properties of Carbon Fibers During Fast Neutron Irradiation," Nature, Phys. Sci., 235, 112 (1972).
20. W. J. Gray, "Neutron Irradiation Effects on Graphite Cloth," Submitted for presentation at the Technology of Controlled Nuclear Fusion, Sept. 21-23, 1976, Richland, Washington.
21. ASTM Recommended Practice E-525, Annual Book of ASTM Standards Part 45.
22. W. C. Morgan, "Notes on the Two-Phase Model for Radiation-Induced Dimensional Changes in Graphites," Carbon, 4, 215 (1966).
23. W. W. Delle, G. Haag, H. Nickel, H. A. Schulze, and R. E. Schulze, "Influence of the Irradiation Induced Graphitization of Graphitic Materials on Their Property Behavior Under Fast Neutron Exposure at High Temperatures," Fourth Conference on Industrial Carbons and Graphite, Soc. Chem. Ind., London (in press).
24. G. L. Tingey, W. C. Morgan, and E. M. Woodruff, Near-Isotropic Graphites For Helium-Cooled Reactors--A Review, BNWL-B-478 (February 1976).
25. G. L. Tingey and W. C. Morgan, Graphite for Helium-Cooled Reactors--A Review, BNWL-1687 (September 1972).
26. J. W. Helm and J. M. Davidson, "Effect of Massive Neutron Exposure on the Distortion of Reactor Graphite," Carbon, 1, 435 (1964).
27. J. W. Helm, "Radiation Effects in Graphite at High Temperatures," Carbon, 3, 493 (1966).

28. J. H. Cox, Jr. and J. W. Helm, "Graphite Irradiations 300°-1200°C," Carbon, 7, 319 (1969).
29. J. W. Helm, Irradiation of Graphite at Temperatures of 300° to 1200°C, BNWL-1056 A (June 1969) and BNWL-1056 B (August 1969).
30. W. J. Gray and A. L. Pitner, "The Increased Lifetime of Graphites Irradiated Above 1200°C," Carbon, 9, 699 (1971).
31. W. C. Morgan and W. J. Gray, High-Temperature Graphite Irradiations: 550 to 1450°C, BNWL-1672 (June 1972).
32. M. R. Everett, L. W. Graham, R. Manzel, and R. Blackstone, "Dimensional and Physical Property Changes of High-Temperature Reactor Graphites, Pyrocarbons, and Fuel Bodies Irradiated at Temperatures in the Range 600-1200°C," Carbon, 9, 417 (1971).
33. R. Blackstone, L. W. Graham, M. R. Everett, and W. Delle, "Irradiation Data on Gilsocarbon Graphites for High-Temperature Nuclear Reactors," Radiation Damage in Reactor Materials, STI/PUB/230 IAEA, Vienna, pp. 534-570 (1969).
34. M. Van den Berg, M. R. Everett, and A. Kingsbury, "The Relationship Between Irradiation Temperature and Dimensional Changes of Nuclear Graphites," 12th Biennial Conference on Carbon, pp. 307-310 (1975).
35. Letter from M. R. Everett to W. J. Gray, dated January 15, 1976.
36. Unpublished data, Dragon Project (April 1974).
37. R. Blackstone, R. Krefeld, W. W. Delle, M. R. Everett, D. L. Leushacke, and H. J. Veringa, "Irradiation Behavior of Gilsocarbon Graphites," 11th Biennial Conference on Carbon, CONF-730601, pp. 292-293 (1973).
38. G. L. Kulcinski and R. W. Conn, "Reduction of Plasma Contamination Effects and First Wall Erosion in Fusion Devices," Nuclear Fusion, 15, 327 (1975).
39. B. J. Wood and H. Wise, "The Reaction Kinetics of Gaseous Hydrogen Atoms with Graphite," J. Phys. Chem., 73, 1348 (1969).
40. A. B. King and H. Wise, "Reaction Kinetics of Hydrogen Atoms with Carbon Films," J. Phys. Chem., 67, 1163 (1963).
41. F. J. Vastola, P. L. Walker, Jr., and J. P. Wightman, "The Reaction Between Carbon and the Products of Hydrogen, Oxygen, and Water Microwave Discharges," Carbon, 1, 11 (1963).

42. P. S. Gill, R. E. Tooney, and H. C. Moser, "Reaction of Hydrogen and Tritium Atoms With Carbon at 77°K," Carbon, 5, 43 (1967).
43. R. K. Gould, "Kinetics of CH₄ Formation from the Reaction of H with Graphite," J. Chem. Phys., 63, 1825 (1975).
44. M. Balooch and D. R. Olander, "Reactions of Modulated Molecular Beams with Pyrolytic Graphite, III. Hydrogen," J. Chem. Phys., 63, 4772 (1975).
45. S. Veprek, M. R. Haque, and H. R. Oswald, "Chemical Erosion of Some Low-Z Materials By Hydrogen Plasma," International Conference on Surface Effects in Controlled Fusion Devices, San Francisco, California, February 16-20, 1976.
46. V. M. Gusev, M. I. Guseva, E. S. Ionova, Yu. L. Krasulin, S. V. Mirnov, and A. V. Nedospasov, Study of Atomization and Blistering of Certain Materials Bombarded With Hydrogen and Helium Ions, ANL-Trans-973 (1974).
47. I. P. Busharov, E. A. Garbatov, V. M. Gusev, M. I. Guseva, Yu. V. Martynenko, Chemical Atomization of Graphite by H⁺ Ions, ERDA-TR-50, Moscow (1975).
48. R. Behrisch and B. B. Kadomtsev, "Plasma Physics and Controlled Nuclear Fusion Research," Proc. 5th Conf., Tokyo, 1974 (IAEA, Vienna, Austria, 1975).
49. J. N. Smith, Jr., C. H. Meyer, Jr., and J. K. Layton, Sputtering Measurements on CTR Materials Using Auger Electron Spectroscopy, GA-Al3665 (Oct. 1975).
50. J. Roth, J. Bohdanský, W. Poschenrieder, and M. K. Sinha, "Physical and Chemical Sputtering of Graphite and SiC by Hydrogen and Helium in the Energy Range of 300 to 6000 eV," International Conference on Surface Effects in Controlled Fusion Devices, San Francisco, California, Feb. 16-20, 1976.
51. S. K. Erents, C. M. Braganza, and G. M. McCracken, "Methane Formation During the Interactions of Energetic Protons and Deuterons With Carbon," *Ibid.*
52. R. Wright, R. Varma, and D. M. Gruen, "Raman Scattering and SEM Studies of Graphite, CVD Pyrolytic and Vitreous Carbon, CVD β and α Silicon Carbide, Silicon, and Germanium Surfaces Bombarded with Energetic Protons, Deuterons, Helium, and Argon Ions," *Ibid.*

53. B. Feinberg and R. S. Post, "Graphite Surface Erosion and Blistering," J. Vac. Sci. Tech., 13, 443 (1976).
54. H. C. Cole, "A High-Current Hall Accelerator," Nuclear Fusion, 10, 271 (1970).
55. V. M. Gusev and Yu. V. Martynenko, Kerchatov Institute of Atomic Energy, private communication.
56. G. A. Beitel, A Feasibility Study of the Use of Graphite in High Vacuum Applications, NASA CR-111829 (1971).

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