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SCOPE OF WORK FOR EVALUATING THE MECHANICAL PERFORMANCE OF EPR FIRST WALL COATINGS

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SCOPE OF WORK FOR EVALUATING THE MECHANICAL PERFORMANCE
OF EPR FIRST WALL COATINGS

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ABSTRACT

An outline is presented for a proposed scope of work to evaluate the mechanical performance of candidate first wall coatings for a Tokamak-type fusion reactor. The goal of the overall program is to provide an adequate coating material and recoating process which can be manufactured by currently available vendors.

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Introduction

Most recent thinking and research on the problems of first-wall coatings for Tokamak-type fusion reactors, such as an Experimental Power Reactor (EPR), have emphasized physics-related concerns of coating interactions with a plasma and its radiation. This has led to research on measurements of interaction cross-sections and sputtering rates of coating materials under limited conditions. While these are necessary and valid first concerns, development of a usable first wall coating also requires investigation of a wide range of thermal, mechanical and physical properties of the coating and substrate. The Argonne National Laboratory's conceptual design (1) utilizes a beryllium coating over stainless steel coolant panels as a first wall covering the vacuum wall. The proposed design lifetime limits for this configuration are 3 to 5 years and 10^6 thermal cycles. These panels would operate at about 450°C and cycle over a 100°C amplitude every 60 seconds during operation. The ANL report indicates that such a thermal history would be the life limiting factor for the first wall. This report outlines a proposed scope of work to evaluate the mechanical performance of candidate coatings. This evaluation would be an integral and important task of an overall coatings development program but should be supplemented by developing design and process specifications.

There are four goals of a development program established to provide a usable first wall material for an EPR:

- (1) to screen available processes and coatings to determine which are the most viable candidates.
- (2) to identify failure modes or processes by studying the bonding mechanisms and the debonding characteristics of the candidate

coatings so that the coating processes and materials can be optimized prior to fabrication of full-sized reactor components.

- (3) to aid in the design of reactor parts by observing the effects of substrate geometry on the ability of each candidate coating to adhere in simulated reactor environments and reducing the observations to design standards.
- (4) to provide information in the form of process specifications necessary for vendor qualification for the supply of reactor components and also to provide the techniques to evaluate these coatings and their reactor performance.

There are a number of coating processes and materials which have been developed and which may be applicable. The primary difficulty is in evaluating how a candidate coating would perform in an EPR environment. The coating and substrate will be exposed to both thermal and mechanical cycling and will accumulate bulk radiation damage. Adherence and cracking resistance will depend upon complex interactions of physical and mechanical properties, operating temperatures, cycling rates, and radiation damage.

Operation of Tokamak reactors at an elevated mean temperature with superimposed temperature cycles would lead to thermal fatigue of first wall structural panels, coatings, and the interface between them. Heat-up of the reactor to a mean temperature could generate large net elastic stresses and some localized plasticity in the walls due to thermal expansion shutdown of the entire structure. From these strains interfacial stresses would develop between coating and substrate due to differences in modulus. Also, thermal expansion mismatch between coating and structural material during heat-up would lead to stresses at the

interface. Over long periods at high temperature, creep in the wall or coating would tend to relieve built-up stresses; these stresses would reform in the opposite direction after cooling during shutdown. The magnitude of all these stresses could be limited by good design using present codes, and the number of these cycles should be relatively small (< 10 per year in a commercial reactor).

A second high cycle mode of thermal fatigue would occur due to high rate thermal shock caused by rapid energy deposition on the coating surface during plasma generation. Rates for this mode of thermal fatigue are on the order of one cycle per minute. Temperature gradients from surface to subsurface generate strain gradients by differential thermal expansion, and this would fatigue both coating and substrate as a thermal gradient formed. Magnitude of the strains in each material would depend on thickness, thermal conductivity, temperature difference, and expansion coefficient. Again differences in expansion coefficient would lead to interfacial stresses between coating and substrate. The magnitude of interfacial stresses could be lessened by the use of multilayer coatings with graduated differences in thermal expansion coefficient.

This program to develop first-wall coatings would not attempt to study in detail thermal fatigue of the first-wall structural material-- at this time 316 stainless steel. Assessment of thermal fatigue behavior of the coating material and its interface, however, should comprise a major part of the development program.

The traditional test techniques to evaluate coating adhesion at room temperature probably will not be indicative of the ability of a coating to withstand the first wall EPR environment. Some complex and expensive tests which more nearly duplicate the EPR conditions will be necessary to

evaluate promising candidate coatings. It is hoped, however, that fundamental understanding of the behavior of coatings might be used to qualify simpler and cheaper room temperature test techniques which could be used by a commercial vendor for quality control.

The focus of any proposed R&D program must be to supply EPR designers with a usable coating process and material which can be provided by currently existing vendors. Recoating and repair capability is also a major performance criterion for any coating material and process development. There must be a balance, therefore, in the proposed work between gathering the necessary engineering data for candidate coatings and conducting sufficient fundamental experiments to insure that all of the coating process and material variables have been optimized to produce the most effective coating. Detailed specifications for coating processes and quality assurance techniques developed in the program would be presented in suitable form to EPR designers and commercial vendors.

Description of a Balanced Coating Mechanical Performance Developmental Program

The development of a first wall coating involves several phases of experimentation in which each phase represents sequentially increased sophistication and cost. As discussed earlier, the most important qualities of a coating are:

- (1) a low erosion rate,
- (2) its ability to maintain mechanical integrity and not debond from the substrate and flake off into the plasma.

The following discussion describes a program to develop coatings with necessary mechanical integrity. The development of low erosion properties is discussed elsewhere³. Such a program would contain three phases of study:

Phase I. Qualitative screening of candidate coatings using simple and inexpensive tests.

Phase II. Quantitative measurement of the mechanical properties of the best coatings resulting from Phase I. This effort would have two directions:

- a. Determination of coating process limits and of the geometric limits for substrate design.
- b. Quantitative analysis of coating/substrate mechanical properties.
- c. Simulation of synergistic effects of thermal, mechanical and radiation damage.

Phase III. Testing of full scale reactor components in which all of the synergistic effects of temperature, stress state and radiation could be evaluated.

Phase I

The first phase is a screening phase. Its purpose is to utilize relatively inexpensive samples and simple test techniques to qualitatively rank a large number of candidate coatings. Initial screening can be accomplished using such standard, quality control oriented tests as the knife test, the twisting or bending test and the adhesive tape pull-away test. These and other simple tests (2) require only small specimens and can be accomplished without special test apparatus. The specimens for these

tests would be in the form of coated stainless steel stamps which have dimensions of about 0.1 x 2 x 5 cm. These tests would primarily eliminate those coatings which are too fragile at room temperature to allow the fabrication and installation of reactor components without significant damage to the coating surface.

Further screening could be accomplished by the use of more quantitative room temperature mechanical tests. Such tests would include:

- (1) 4-point bend tests
- (2) tensile tests
- (3) torsion tests
- (4) flyer-plate stress wave tests

Each of these tests would require that the candidate coatings be applied to steel specimens which have been machined to the dimensions dictated by the specific test. All of these tests would be conducted for the purpose of determining the adhesion strength and cracking resistance of candidate coatings; however, since the EPR first wall material will experience primarily cyclic loading, some simple fatigue tests should be conducted as part of the screening phase of the test program. The cyclicly-loaded cantilever beam test at room temperature is a simple test which could be conducted at high frequencies. This method of fatigue loading is preferred over simple thermal cycling since thermal lag of the sample limits the test frequency and thus greatly lengthens the duration of each test.

All of the tests thus far described for Phase I would be at room temperature. For many coatings whose properties do not change significantly up to 500°C, room temperature mechanical cycling would be adequate for screening purposes. The added cost of high temperature testing would be

justified if the properties of either the coating or the substrate change greatly with temperature. These tests could include mechanical fatigue at elevated temperature or thermal cycling about a mean elevated temperature. Candidate coatings for use at temperatures in excess of 1000°C would likely perform differently at the operating temperature than at room temperature. Elevated temperature testing of these coating materials as part of Phase I may be justified. Thermal cycling fatigue about a mean elevated temperature could be accomplished by several techniques: by pulsed radiant heating, pulsed laser beam, pulsed RF generation, or by using a rotating disc subjected to local heating.

All of the samples which are prepared for Phase I screening should be saved and catalogued into an archival storage system. This procedure would allow all of the candidate coatings to be ranked by quality first without excessive pre-analysis. Utilizing archival samples would result in detailed analysis of only the most promising candidate coatings.

Phase II

The screening of coating materials and processes done in Phase I will produce some workable number of candidate coatings. Once the list of candidates has been determined, vendor contracts should be initiated for production of the samples to be tested in Phase II. This second phase of testing is an intermediate phase between the initial screening of coatings and the construction of reactor-size components. Two kinds of tests need to be conducted during Phase II:

- (1) Tests which define process limits or geometric limits using samples having complex substrate geometries. These samples would be exposed to thermal/mechanical/radiation histories

to determine such design parameters as the minimum allowable radius of substrate curvature.

- (2) Mechanical properties tests for analysis of the debonding and flaking processes. From quantitative measurements of the effects of temperature, stress, gaseous environment, and radiation damage on the coatings, the best of the coatings could be determined and vendor process variables could be altered to optimize the coating performance.

A large number of experimental techniques could be used to accomplish the purposes of Phase II testing. One possible general outline of experimental and analytical work is shown here:

- (1) Conduct thermal cycling about an elevated mean temperature in a simulated environment.
 - (a) Use complex, larger specimens to evaluate effects of stress concentrations (holes, corners, grooves, notches)
 - (b) Correlate behavior of room and elevated temperature mechanical fatigue tests to thermal cycling results
 - (c) Study the effects of weldments on coatings and the effects of recoating processes over scratches.
 - (d) Investigate influence of possible gaseous species, particularly molecular and atomic hydrogen, on coating life.
- (2) Measure physical properties for use in analytical codes, of deposited coatings at temperature (before and as a function of irradiation). To include:

- (a) Thermal conductivity
 - (b) Emittance
 - (c) Thermal expansion
 - (d) Elastic modulus
 - (e) Fracture strength
 - (f) Stress relaxation
 - (g) Plasticity
 - (h) Residual stresses
 - (i) Thermal shock properties
- (3) Perform qualitative and quantitative microscopy
- (a) Study changes at the interface
 - (b) Study the structure of both substrate and coating
- (4) Conduct analytical code development:
- (a) to predict stresses and strains before and after cycling at elevated temperatures.
 - (b) to predict the mechanical life.
 - (c) to correlate high and low temperature behavior.
- (5) Develop techniques to detect delamination of the coating.
- Several potential NDT methods which could be pursued are listed here.
- (a) Measurement of heat transfer through a substrate and coating by scanning laser heating with infrared sensors.
 - (b) Measurement of acoustic resonance of the coating by photoacoustic spectroscopy.
 - (c) Measurement of surface topography by laser holography.

As in Phase I, samples prepared for Phase II study should be kept in archival storage.

Mechanical Property Effects of Radiation Damage

Significant radiation damage is expected to be experienced by the first wall which will affect the mechanical properties of both the coating and the substrate materials. The integration of radiation damage effects into the initial experiments of Phases I and II has not been discussed since there is presently no test facility available which adequately duplicates the EPR environment. It is expected that the effects of temperature, stress, molecular or atomic hydrogen, and radiation damage will be highly synergistic. Accordingly, radiation damage of some form should be included as an experimental variable as early as possible. Exposures to the most damaging species (ions, neutrons, etc.) for specific coatings could be provided by different facilities. This would necessitate continually evaluating alternate radiation testing facilities during the course of the coating development program.

The initial test development work performed in Phases I and II would allow design of the most suitable test specimens to undergo irradiation and subsequent mechanical testing. From radiation damage studies, such quantities would be determined as:

- (1) The most important radiation damage processes for specific coatings as a function of species, temperature, fluence and dose rate,
- (2) A knowledge of degradation rates and mechanisms to allow decisions on the feasibility of various recoating processes.

Phase III

The third phase of testing EPR first wall coating materials concerns the testing of full scale reactor components in the reactor environment. A large scale test facility will be necessary to evaluate the coating processes to be used for full sized components and to study the thermal fatigue behavior of large structures. Remote application and touch-up techniques will be developed that are suitable for full sized components. Another important part of Phase III study will be the correlation of the simple measuring techniques developed during Phase I with the sophisticated techniques developed in Phase II to establish relatively simple quality control procedures to be used by the coating vendors. The exact nature of the work done in Phase III will be strongly dependent on the nature of the specific coatings chosen for use in the EPR.

Conclusion

The result of the coating development program should be the selection of an adequate coating material and recoating process which can be manufactured by currently available vendors. At the completion of the developmental program, the coating process and the quality assurance techniques will be turned over in usable form to the commercial vendors.

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