MECHANICAL PROBLEMS
RELATED TO THE TREATMENT OF REACTOR MATERIALS

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SUMMARY

The main objectives of this work are twofold: Firstly, to investigate the effect of fast neutron irradiation on the mechanical properties of cladding materials. Six alloys, generally used as cladding materials in nuclear fuels, were used in these investigations, namely, zircaloy-2, zircaloy-4, zirconium-2.5 wt% Nb, AISI Type-304, AISI Type-316 and AISI Type-347. Secondly, to study the decladding of nuclear fuel by the rolling-straightener technique.

The background information relevant to irradiation hardening was reviewed with particular emphasis on zirconium-based alloys and stainless steels. The review showed discrepancy in reported data, and lack of informations especially at elevated-temperature irradiations. Also, the various methods used for mechanical decladding have been reviewed and assessed. The assessment indicated that the rolling-straightener technique is the simplest from the operational and maintenance point of view, as well as, posing the least amount of contamination problems.

A theoretical approach was followed to formulate the equation of radial deformation, in order to eliminate the unphysical uncertainties inherited in a previous treatment of

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this equation. The optimum values of the rolls inclination and the total length of contact between machine rolls and work-piece, were extracted by studying the nature of the hyperbolic surfaces of the rolls.

Experimental work was carried out to investigate the irradiation hardening in zirconium-based alloys and stainless steels, and to study the feasibility of the rolling-straightener technique for the decladding of cylindrical nuclear fuel. Both low-and elevated-temperature irradiations were performed to various fast neutron fluences. Special attention was given for accurate reporting of neutron flux and constant temperature during irradiation, in order to eliminate any discrepancy in expected results. The low-temperature irradiations simulated the conditions of experimental and research reactors, while the elevated-temperature irradiations simulated the conditions of power reactors of the pressurized water type. For elevated-temperature irradiation, the effect of hydrogen pick-up in zircaloy-2 and zircaloy-4, on the mechanical properties was studied.

Test samples of dummy fuel elements were prepared and tested in a rolling-straightener machine of Type-WRUN to verify the equation of radial deformation, and to study the

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effect of fuel and clad parameters on radial deformation.

The following conclusions were drawn from the obtained results:

(1) Considerable hardening due to fast neutron irradiation resulted in all materials investigated. The change in YS due to neutron exposure obayed a formula in the form:

$$\Delta \sigma_a = C\ (\Phi t)^n$$

The constant "C" was found to depend on the matallurgical conditions of the material before irradiation, while the exponent "n" was dependent on the material and the temperature of irradiation. The value of "n" was found to be 0.33 for zircaloy-2, 0.4 for zircaloy-4, 0.44 for zirconium-2.5 wt% Nb and 0.5 for stainless steels, irradiated at low-temperature, while at elevated-temperature irradiation, "n" was 0.1 for both zircaloy-2 and zircaloy-4.

(2) The hydrogen pick-up in zircaloy-2 as a result of exposure to steam at irradiation conditions, was small and did not significantly affect the mechanical properties.

(3) The feasibility of decladding cylindrical fuel rods by the rolling-straightener technique was ensured. The technique was found to depend, significantly, on several factors,

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Chapter - 1

INTRODUCTION

Nuclear reactor technology has demanded the use of materials with certain physical and mechanical properties to meet service conditions in reactor core environment. In nuclear fuel element, which is the most important component of a nuclear reactor core, the fissionable material is cladded with a suitable non-fissionable material to prevent corrosion of the fuel by the coolant, and to prevent fission gas release. The cladding materials should satisfy rigid nuclear and metallurgical considerations such as low-capture neutron cross-section, low induced radioactivity, good corrosion resistance to coolant, and good mechanical properties such as high yield and tensile stresses. The most important cladding materials are zirconium-based alloys and stainless steels, which has been used in Boiling Water Reactors (BWR), and Pressurized Water Reactors (PWR).

Being exposed to an environment of high energitic neutrons or fast neutrons, the materials should be able to possess irradiation stability and to withstand irradiation effect. The mechanical properties of cladding materials are significantly influenced by exposure to fast neutrons. The hardness and yield

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strength are increased; this is known as irradiation hardening. Furthermore, irradiation causes a reduction in ductility and an increase in brittlness. A quantitative determination of these effects is required for reactor design purposes and is also important for understanding the mechanisms of irradiation hardening.

The effect of irradiation on the tensile properties of zirconium-based alloys and stainless steels has been investigated at various fast neutron doses, irradiation temperatures, and metallurgical conditions. A critical review (Chapter - 2) has shown that there is a considerable scattering of the data, and thus the dependence of irradiation hardening on the neutron dose cannot be determined accurately. The scattering may be attributed to the inaccuracies of measuring and reporting neutron flux, and the use of materials with various metallurgical and mechanical properties. Furthermore, the dose range covered in a single experiment was not in many cases large enough.

One of the purposes of this work was to design and perform careful irradiation damage experiments in which the flux is monitored and measured accurately. The effect of fast neutron exposure on yield strength, ultimate tensile strength, elongation, and hardness was determined at low-and high-temperatures

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of irradiation for zircaloy-2, zircaloy-4, zirconium-2.5wt%Nb, and stainless steels AISI Type-304, AISI Type-316, and AISI Type-347.

Spent or burnt fuel elements, after being removed from nuclear reactor, are reprocessed chemically to recover the valuable fertile and fissionable materials. Prior to chemical reprocessing, decladding of spent fuel elements is important economically, because it increases processing rate, and improves the yield of fissile and fertile materials. A good fuel element design should take into consideration the ease of decladding and reprocessing. The principal methods used for clad removal are based, mainly, on chemical and mechanical methods or by the chop-leach method, which is a combination of both.

Mechanical decladding methods overcome problems of chemical and chop-leach methods such as the difficulties in liquid waste disposal, contamination problems, and the loss of fissile and fertile materials. Furthermore, reprocessing operations are improved by reducing chemical consumption and number of processes. The method produces solid radioactive waste which can be handled and stored more easily than liquid waste produced by other methods. Mechanical decladding would also permit high density charging of the dissolvers, thus allowing

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high dissolving rates to be obtained.

The different methods used for mechanical decladding has been critically reviewed and assessed (Chapter - 2). One of the important and promising methods is the decladding by the rolling-straightener technique. This method is based on the radial deformation of the clad, caused by passing the fuel element through special rolls. This method is flexible and simple from the operation and maintenance points of view, as well as posing the least amount of contamination problems.

The second purpose of this work is to study the factors affecting radial deformation, and to develop an equation relating radial deformation to both machine and cladding materials parameters, and to verify this experimentally on dummy fuel elements, as well as, to assess the effect of irradiation damage of cladding materials on the feasibility of this method.

This thesis consists of seven chapters. Chapter - 2 deals with the background information and literature review relevant to irradiation damage and irradiation hardening with particular emphasis on zirconium-based alloys and stainless steels. The various methods used for mechanical decladding with special attention to the rolling-straightener technique has been

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reviewed and assessed. In chapter - 3, the theoretical reformulation of the equation relating radial deformation to machine and material parameters has been described. The experimental technique and materials used in the investigation are discussed in chapter - 4. The results of the effect of irradiation on mechanical properties and the factors affecting mechanical decladding are given in chapter - 5. Finally, chapter - 6 contains the discussion of the results, and chapter - 7 includes a summary and conclusion of results.

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Chapter - 2

BACKGROUND INFORMATION AND LITERATURE REVIEW

2.1. INTRODUCTION:

Cladding materials constitute a very important item of nuclear reactor components. The effect of irradiation on the mechanical properties of cladding materials is necessary for the evaluation of their performance under service conditions. Removal of the clad from the spent fuel element by mechanical means (mechanical decladding) is an attractive head-end process before chemical reprocessing.

This chapter is divided into three sections. In the first section, the main characteristics of reactor components with emphasis on cladding materials are summarized. The second section deals with the various theories of irradiation damage and irradiation hardening. Furthermore, the literature review on irradiation hardening in zirconium alloys and stainless steels, in the last 15 years, is included. A critical review of mechanical decladding of nuclear fuel elements is given in last section.

2.2. NUCLEAR REACTOR COMPONENTS:

A nuclear reactor may be defined as a device, in which nuclear energy is liberated as a result of chain reaction

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