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A multi-stage wear model for grid-to-rod fretting of nuclear fuel rods

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ABSTRACT

The wear of fuel rod cladding against the supporting structures in the cores of pressurized water nuclear reactors (PWRs) is an important and potentially costly tribological issue. Grid-to-rod fretting (GTRF), as it is known, involves not only time-varying contact conditions, but also elevated temperatures, flowing hot water, aqueous tribo-corrosion, and the embrittling effects of neutron fluences. The multi-stage, closed-form analytical model described in this paper relies on published out-of-reactor wear and corrosion data and a set of simplifying assumptions to portray the conversion of frictional work into wear depth. The cladding material of interest is a zirconium-based alloy called Zircaloy-4 which rubs against dimples or springs on the supporting grid which may be composed of the same or a different alloy. The model involves an incubation stage, a surface oxide wear stage, and a base alloy wear stage. The wear coefficient, which is a measure of the efficiency of conversion of frictional work into wear damage, can change to reflect the evolving metallurgical condition of the alloy. Wear coefficients for Zircaloy-4 and for a polyphase zirconia layer were back-calculated for a range of times required to wear to a critical depth. Inputs for the model, like the friction coefficient, are taken from the tribology literature in lieu of in-reactor tribological data. Concepts of classical fretting were used as a basis, but are modified to enable the model to accommodate the complexities of the PWR environment. Factors like grid spring relaxation, pre-oxidation of the cladding, multiple oxide phases, gap formation, impact, and hydrogen embrittlement are part of the problem definition but uncertainties in their relative roles limits the ability to validate the model. Sample calculations of wear depth versus time in the cladding illustrate how GTRF wear might occur in a discontinuous fashion during months-long reactor operating cycles. A means to account for grid/rod gaps and repetitive impact effects on GTRF wear is proposed.

1. Introduction

Meeting society's energy needs requires a portfolio of technologies whose mix and viability is dictated by economic, geopolitical, environmental, and technological factors. While there is interest in wind, tidal, hydropower, and solar energy, the safe and reliable operation of nuclear plants is essential if they are to contribute to the world's energy portfolio. Consequently, the elimination or minimization of wear and surface damage that results from the operation of certain key components of nuclear plants enables that goal.

The core design used in United States pressurized water reactors (PWRs) typically consists of over 50,000 vertically-bundled cylindrical fuel rods. They are typically 4–5 m in total length and the rods are separated by a series of metal spacer grids containing what are known as dimples and springs which contact the cladding and hold it in place. Pressurized water that can exceed 350 °C enters the bottom of the vessel and flows upward through the fuel rod bundles. The turbulence from flow induced vibrations (FIV) in the structure, in particular at the contact points between the spacer grid and the fuel rods. Grid-to-rod fretting (GTRF) may produce wear of the rod cladding that if not caught early enough can lead to the exposure of the fuel pellets (such situations are called ‘leakers’). Leakers are a significant concern for PWR designers and plant operators [1]. In fact, it has been estimated that upwards of 70% of the leakers result from GTRF wear [2].

Efforts have long been underway to better understand GTRF processes, but the inability to perform controlled wear experiments inside working nuclear reactors has limited the ability to test hypotheses or validate GTRF wear models directly. The current work is a small part of a larger U.S. Department of Energy project to predict the effects of changing a light water nuclear reactor's operating conditions on its materials and structures using advanced computer models [3,4]. The GTRF wear activity began with a definition of a single grid-rod tribosystem and then attempts to model its wear in a straightforward, albeit semi-empirical way.

A three-stage engineering GTRF wear model is presented here. Modeling complex tribosystems like GTRF must of necessity

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involve simplifying assumptions, yet the form of the model should allow for future improvement as the input variables and their changes with time become better known. The model presented here is intended to portray the time-dependent wear history of a single fuel rod within a larger bundle as it oscillates against a dimple or spring. A parallel effort at the Massachusetts Institute of Technology, which is not further described here, is employing a first-principles, discrete element modeling approach to calculate GTRF wear coefficients [5]. It is hoped that the wear model described here, and which uses a simplified quasi-empirical approach, can later incorporate the results of more fundamental work on nano-scale fretting wear mechanisms, like those at MIT.

2. Problem definition and complicating factors

The fuel rods in a PWR core are supported by a series of regularly-spaced grids, the design details of which are proprietary to the manufacturer and generation of the design. A simplified schematic arrangement of one fuel rod in a grid cell is given in Fig. 1. Two opposing dimple/spring couples, at 90° to each other, hold the rod in place (only one couple is shown in Fig. 1). Although certain design features (not shown) create eddies in the flow, the general direction of coolant water flow is parallel to the rod axis in Fig. 1. Flow-induced oscillations cause the rod to fret against the grid. The direction of fretting is commonly transverse or oblique to the rod axis. This was determined from examination of fretting wear scars on fuel rods or unfilled tube specimens that are subjected to out-of-reactor tests and from the literature (for example, see Refs. [6–8]). Differences in wear scar shapes and depth profiles reflect differences in dimple and spring designs (see Figs. 2 and 3).

During reactor operation, the spring pre-load tends to relax causing the normal force to decrease with time. Flow-induced vibrations in the normal force are superimposed upon the spring force. Therefore, the normal force on the contact is the sum of the remaining spring load and flow-induced normal load fluctuations.

The PWR environment promotes corrosion, and sometimes a rim of hydrides forms near the water-side surface of the Zr alloy cladding [10,11]. Exposure to high neutron fluences at high burn-up rates can also result in a layering of zirconium oxides on the cladding surface [12]. A relatively thin tetragonal zirconium oxide (ZrO_2) phase forms first on the base metal, and then a more brittle monoclinic phase forms on top of that. The tetragonal phase tends

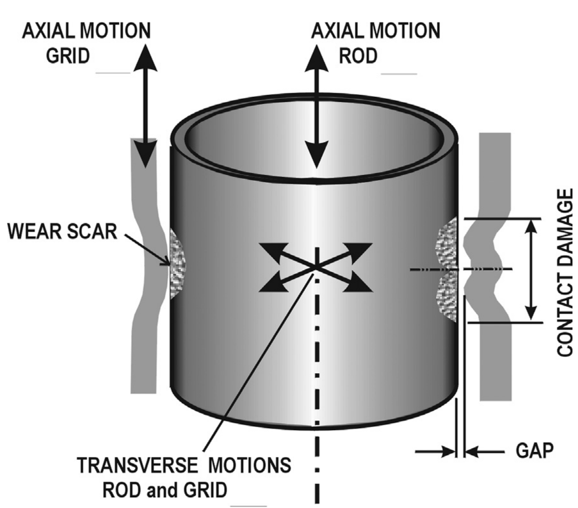

Fig. 1. Simplified contact geometry showing a hollow tube (normally filled with fuel pellets) captured between a dimple (right)–spring (left) pair. Depending on conditions, a gap can form at contact locations.

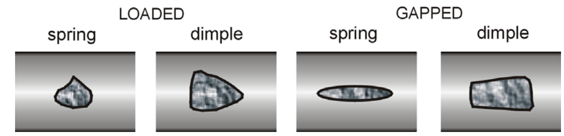

Fig. 2. Typical GTRF wear scars. 'Loaded' refers to continuous contact and 'Gapped' refers to intermittent contact. Shapes are based on those shown in Ref. [9].

to be more wear resistant than the monoclinic phase [13,14]. When the brittle, monoclinic phase grows too thick, it can crack, exposing the metal and leading to the formation of new tetragonal phase. Thus, the microstructure of the materials in contact zone can change properties over time, and that suggests that the wear coefficient would not remain constant during the days, weeks, and months of operation as it wears through the layers. The multi-stage modeling approach does not assume a constant wear rate, but rather presumes that the wear coefficient changes during the subsequent stages in the wear history.

Finally, the question arises as to where in the core assembly (near the top, bottom, sides, etc.) the most problematic conditions for leaker-producing wear exist. With over 50,000 rods and multiple contact points along each rod, the choice of a critical contact location for modeling purposes is non-trivial. Proprietary plant inspection reports have shown that certain locations are more prone to GTRF than others, but these depend on the design and operating conditions. To be conservative, one might assume a worst-case location and a set of worst-case contact conditions.

Discussions within the CASL GTRF project team [4], coupled with a bibliographic review of the literature (e.g., [6–8]) and fretting wear concepts in general (e.g. [15,16]), has led to the development of the three stage GTRF engineering (semi-empirical) wear model described here. The cladding material of interest is an alloy called Zircaloy-4 (UNS designation R60804). This alloy, which has served as a workhorse for the nuclear industry for decades, continues to evolve into more recent variants. Zircaloy-4 was originally developed to provide a combination of structural strength, aqueous corrosion resistance, high thermal conductivity, and low neutron cross-section [17]. Its nominal composition in weight percent is: 1.4 Sn, 0.2 Fe, 0.1 Cr, 0.12 O, bal. Zr [18].

3. Form of the GTRF model

The GTRF engineering wear model (EWM) presumes three sequential stages in the wear life. The first stage ('Stage 0') is a 'pre-wear' (incubation) period where there is either no relative motion (fully clamped) or the contacts are separated by a gap. The second stage ('Stage 1') depicts the wear-through of the oxide film on the cladding. This film may be pre-grown or formed during exposure. The third stage ('Stage 2') depicts wear into the Zr alloy once the oxide layer has been removed. This final stage is likely to have the highest rate of wear because the underlying alloy has been exposed to the core environment and it may also be embrittled by hydride formation and neutron exposure.

Development of the initial EWM model began with the following assumptions:

(1) A single contact is being modeled and it is located at a position in the rod assembly that is most susceptible to GTRF wear.
(2) The approach does not differentiate whether the contact is between the cladding and a dimple or a spring. It is basically a curved surface against a flat surface.
(3) The wear-critical component is a thin-walled cylindrical Zircaloy-4 tube (the cladding). The wear of the grid is not being modeled. While the energy available to produce wear is split between the partners in a tribo-contact, this model