Annals of Nuclear Energy 90 (2016) 234–239

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Technical note

Linear heat generation rate for breaking plastic strain limit of cladding in a BWR fuel rod type

Hector Hernandez-Lopez *, Marco A. Lucatero [1]

Instituto Nacional de Investigaciones Nucleares, Carr. Mexico-Toluca s/n (km 36.5), La marquesa, Ocoyoacac, Mexico 52750, Mexico

ARTICLE INFO

Article history:
Received 25 September 2015
Received in revised form 8 December 2015
Accepted 10 December 2015
Available online 28 December 2015

Keywords:
Fuel rod
LHGR
Thermomechanical behavior

ABSTRACT

The linear heat generation rate (LHGR) is calculated for a BWR fuel rod type as a burnup function that breaks the plastic strain circumferential limit of cladding in nominal operation and steady state. The evaluation of the LHGR as a burnup function of fuel rod is performed under the condition of which the values of the circumferential plastic strain of the cladding exceed in a 10% of the limit value operation of 1%.

The results show that for burn up between 0 and 16,000 MWd/tU there is 160.8 W/cm as minimum margin between LHGR peak for maximum operation (439.6 W/cm) and LHGR calculated to reach 1.1% of circumferential plastic cladding strain, considering a factor peaking power of 1.40. For a burn up of 20,000 MWd/tU and 60,000 MWd/tU there are margins of 150.3 and 298.6 W/cm, respectively. The calculations are carried out with codes FEMAXI-VI and RODBURN.

1. Introduction

Two parameters describing the thermo-mechanical behavior of fuel rods composing the fuel assemblies in the BWR reactor core are the following: the maximum linear heat generation rate (MLHGR) and the maximum average planar linear heat generation (MAPLHGR). The MLHGR is determined by the analysis of the limits of thermo-mechanical design for a particular fuel assembly. The MAPLHGR in particular is obtained from the average LHGR or from each fuel rod of operation as a burn up function from which the thermo-mechanical limit value is selected.

The thermo-mechanical limits of fuel rods in operation are established (FSAR, 1979) to assure that during nominal operation and anticipated operational occurrences (transitory) of the reactor, the fuel stays within limits of the thermo-mechanical design of fuel rods. These operational limits define the maximum allowed levels of operating power of the fuel pellet as a burnup function.

In order to prevent the cladding failure during the operation of the reactor, due to excessive strain in cladding, caused by the internal pressure increase by the accumulation of released fission gases into the gap of fuel rod and by thermal and mechanical strain in fuel pellet, the limit of 1% in the circumferential plastic strain for zircaloy cladding have been established in NEDO-33270 (2007).

Analysis of linear heat generation rate in a fuel rod is burned function, since it is one of the parameters that largely are reflected in fuel performance. Since it changes seen in the concentration of fissile materials and fission products. And, changes in physical properties of materials and variation in the density of the pellet, embrittlement of the cladding and is particularly of utmost importance changes in the plasticity of the cladding as a result of variations in the power produced in the fuel.

In this process, the linear heat generation rate (LHGR) is calculated for a BWR fuel rod type as a burnup function that breaks the limit of the circumferential plastic strain of the disguised one in nominal operation of the fuel rod. The results are compared with the LHGR in operation as a burnup function for this fuel rod type established by the manufacturer. The calculations are carried out with the codes that have been developed in the Japan Atomic Energy Agency (JAEA) FEMAXI-6 (Suzuki and Saitou, 2005) and RODBURN (Uchida and Saitou, 1993).

2. Codes description

2.1. RODBURN code

RODBURN is a simplified and convenient burning analysis code for LWR fuel rods (Uchida and Saitou, 1993). This code calculates the power density profile in the radial direction of pellet as a function of average burnup and concurrently calculates the generated amounts of fission products and He.

Irradiation of fuel to high burnup causes considerable difference in power distribution the initial state. Particularly in the radial

* Corresponding author. Tel.: +52 55 53297200x12497; fax: +52 55 53297301.
E-mail addresses: hector.hernandez@inin.gob.mx (H. Hernandez-Lopez), marcoa.lucatero@inin.gob.mx (M.A. Lucatero).
[1] Tel.: +52 55 53297200x12497; fax: +52 55 53297301.

http://dx.doi.org/10.1016/j.anucene.2015.12.005
0306-4549/

direction, peaking of power density, and hence of burnup at the periphery causes a microstructural change known as the rim effect. To provide a simple analytical tool for dealing with such power or burnup distribution, a multi-region burnup analysis code RODBURN has been developed. RODBURN incorporates the actinide-related part of the burnup analysis code ORIGEN (Bell, 1973) as the central routine and also the resonance integral code RABBLE (Kier and Robba, 1967) for calculating the localized plutonium production. Calculations on some high-burnup experimental fuels have revealed that the code can reproduce the radially-localized burnup distributions in fuels having various initial enrichments.

RODBURN has several types of default profile of power distribution. RODBURN does not perform a so-called neutron transport calculation which is conducted by some other dedicated burning analysis codes, such as PLUTON or MICROS.

2.2. FEMAXI-6 code

A light water reactor fuel analysis code FEMAXI-6 is an advanced version which has been produced by integrating the former version FEMAXI-V with numerous functional improvements and extensions. In particular, the FEMAXI-6 code has attained a complete coupled solution of thermal analysis and mechanical analysis, enabling an accurate prediction of pellet-clad gap size and PCMI in high burnup fuel rods. Also, such new models have been implemented as pellet-clad bonding and fission gas bubble swelling, and linkage function with detailed burning analysis code has been enhanced. Furthermore, a number of new materials properties and parameters have been introduced. With these advancements, the FEMAXI-6 code has been upgraded to a versatile analytical tool for high burnup fuel behavior not only in the normal operation but also in anticipated transient conditions.

In LWR fuel rods, the interactions among thermal, mechanical and chemical conditions caused by irradiation depend on power levels and their variation with time, power history and burnup. JAEA (Japan Atomic Energy Agency, formerly Japan Atomic Energy Research Institute) developed fuel performance codes such as FEMAXI-III, FEMAXI-IV, FEMAXI-IV (ver.2), for the analyses of changes in thermal and mechanical conditions and their interactions in low and medium burnup regions of a single fuel rod during a normal operation and in an anticipated transient period. For the analysis of high burnup fuel behavior, FEMAXI-V has been developed on the basis of FEMAXI-IV.

Analytical scope of FEMAXI-6 covers normal operation conditions and transient conditions as well such as load-following and rapid power increase, and also boiling transition of BWR fuels. However, it does not cover such accident conditions as RIA and LOCA.

Taking advantage of the experience gained from the development of codes up to FEMAXI-V, the advanced version FEMAXI-6 was developed, in which the code structures were revised and new functions were incorporated. Table 1 shows the target phenomena of FEMAXI-6. As material properties including those for MOX fuels and Gd-containing UO_2 fuels, those available in open literatures were adopted as much as possible.

FEMAXI-6 consists of two main parts: one for analyzing the temperature distribution, thermally induced deformation, and fission gas release, etc. (hereafter called "thermal analysis part"), and the other for analyzing the mechanical behavior of the fuel rod (hereafter called "mechanical analysis part").

3. Procedure of calculation

The calculation method is developed as below is describe:

Table 1
Phenomena analyzed by FEMAXI-6.

	Thermal process determining temperature distribution	Process with mechanical displacement
Pellet	Thermal conduction. (heat flux distribution) fission gas release	Thermal expansion, elasticity, plasticity, creep, cracking, relocation, densification, swelling, hot-press
Cladding	Thermal conduction. Waterside corrosion	Thermal expansion, elasticity, plasticity, creep, irradiation growth
Fuel	Gap thermal conduction (mixed gas, contact, radiation), cladding surface heat transfer, gap gas flow	Mechanical interaction between pellet and cladding, friction, bonding

– First, a simulation of the thermal behavior of the fuel rod with FEMAXI code is performed, using the option of taking Robertson model (IFLX = 0) for power profile.
– Secondly, the RODBURN code simulation is performed for calculating burned and distribution of neutron fluxes considering the maximum temperature attained in the previous simulation.
– Thirdly, again is carried out an execution of FEMAXI code with the RODBURN results option (IFLX = −2). Taken into account that exists the burnup file generated by RODBURN code.

Fig. 1, the calculation scheme with FEMAXI and RODBURN codes is shown. Also, in Fig. 2, the code data flow scheme for each code is shown.

The evaluation of the LHGR as a burnup function of the fuel rod is performed under the condition that the values of the circumferential plastic strain of the cladding exceed in 10% the thermo-mechanical limit value operation of 1%. The calculations are taken assuming that for each burnup step the fuel rod is operating with the same linear power, in a steady state to nominal power condition with the option of elasticity calculations, the normal calculations of temperature, and the mechanical analysis for the overall length of the fuel rod.

Due to the restriction of the number of admitted axial segments (12 maximum) by code RODBURN, a distribution or form of axial power given for ten nodes is used, corresponding to the spectral shift at the beginning of the cycle. The axial distribution of power is shown in Table 2.

The calculations are performed for a radial peaking power factor of 1.40, which is used in calculations of the stress produced by loads and internal pressure in the cladding of the fuel rod.

4. Geometric model and axial distribution

The fuel rod consists of two regions of natural uranium located to the ends, and a region with 4.9 $^{w/0}$ of ^{235}U enrichment. The geometric model of RODBURN of rod adjusts to 10 axial segments, two correspond to the natural uranium regions and the remaining eight are of the enriched uranium region. The selection of 10 axial segments goes according to axial distribution of the selected power. For the geometric model of FEMAXI, 25 axial regions of 15.24 cm were considered each, which agree with the considered nodes in the simulation of operation with 3 natural uranium regions and 22 regions with enrichment of 4.9 $^{w/0}$. This can be observed in Fig. 3 and the Table 3 shows the fuel rod geometric data.

5. Results

Simulating the behavior of a fuel rod to different linear heat generation rate peak was conducted from 350 W/cm to 850 W/cm in order to establish levels are reached burnup before arriving