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**NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS**

NEA/CSNI/R(2011)10
Unclassified

Studsвик Cladding Integrity Project (SCIP)

Executive Summary

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The committee's purpose is to foster international co-operation in nuclear safety amongst the NEA member countries. The CSNI's main tasks are to exchange technical information and to promote collaboration between research, development, engineering and regulatory organisations; to review operating experience and the state of knowledge on selected topics of nuclear safety technology and safety assessment; to initiate and conduct programmes to overcome discrepancies, develop improvements and research consensus on technical issues; and to promote the co-ordination of work that serves to maintain competence in nuclear safety matters, including the establishment of joint undertakings.

The clear priority of the committee is on the safety of nuclear installations and the design and construction of new reactors and installations. For advanced reactor designs the committee provides a forum for improving safety related knowledge and a vehicle for joint research.

In implementing its programme, the CSNI establishes co-operate mechanisms with the NEA's Committee on Nuclear Regulatory Activities (CNRA) which is responsible for the programme of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with the other NEA's Standing Committees as well as with key international organisations (e.g., the IAEA) on matters of common interest.

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**The OECD/NEA
Studsvik Cladding Integrity Project (SCIP)
Executive summary**

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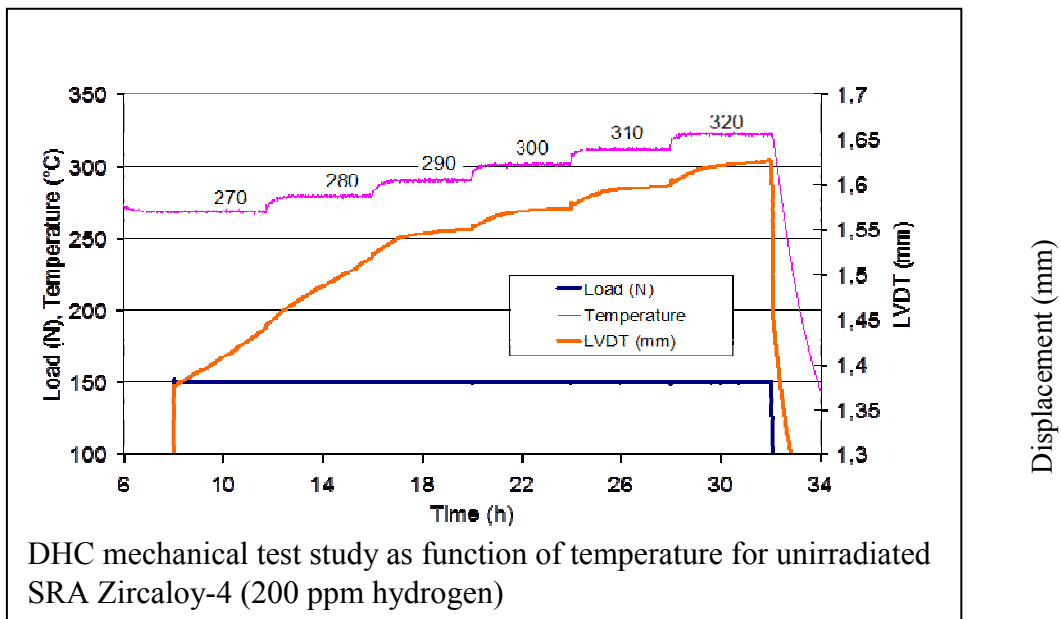
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INTRODUCTION AND SUMMARY

The SCIP programme¹ has generated extensive experimental data on irradiated BWR and PWR claddings by conducting; ramp testing of 11 rodlets, comprehensive nondestructive examinations (NDE), destructive examinations (DE), mechanical testing and extensive microstructural characterization by means of SEM and TEM. With respect to PCI, a modified mandrel testing technique to study iodine induced stress corrosion cracking (ISCC) under well controlled test conditions, was developed and mechanical test techniques were modified to better simulate the in-reactor behavior.

The extensive amount of data has been used to improve the understanding of the fuel rod behavior and the fuel cladding failure mechanisms: Pellet Cladding Interaction (PCI), Hydride Embrittlement (HE) and Delayed Hydride Cracking (DHC), fulfilling the overriding objective of the project, which was to improve the understanding of the dominant failure mechanisms for LWR fuel cladding that can arise during normal operation or anticipated transients. Furthermore, a DHC model has been developed, critical DHC parameters were identified, a PCI screening/simulation test method developed and high burnup (BU) fuel rod behavior during ramp tests studied.



¹ Studsvik Cladding Integrity Project (SCIP) was initiated in 2004 as an OECD/NEA project with Studsvik Nuclear as the operating agent. Since the start 27 signatories from 13 countries have joined the program representing more than 40 organizations (nuclear safety organizations, vendors, utilities and research laboratories)

THE PROJECT

The overriding objective of the project was to improve the understanding of the dominant failure mechanisms for LWR fuel cladding that can arise during normal operation or anticipated transients, focusing on high burnup claddings.

Three failure mechanisms were studied within three corresponding Project Tasks and the driving force for the failure mechanism was studied separately in Task 0.

0. PCMI (Pellet Clad Mechanical Interaction) from power transients, ramp tests, presented as stress and strain data as function of power, time and fuel properties
1. Pellet-clad interaction (PCI): stress corrosion cracking (SCC) initiated at the cladding inner surface under the combined effect of the mechanical loading and chemical environment caused by an increase in the fuel pellet temperature during a power increase.
2. Hydrogen embrittlement (HE): time independent fracture of existing hydrides.
3. Delayed hydride cracking (DHC): time dependent crack initiation and propagation through fracture of hydrides that form ahead of the crack tip.

Task 0: PCMI - Driving force for fuel failures

The objective was to obtain a relationship between cladding residual strain and Linear Heat Rate (LHR) as a function of burnup level and hold time, based on experimental data. The obtained data can be used to get a rough estimation of maximum stresses and strains in the short ramp tests and residual strain evolution as a function of hold time.

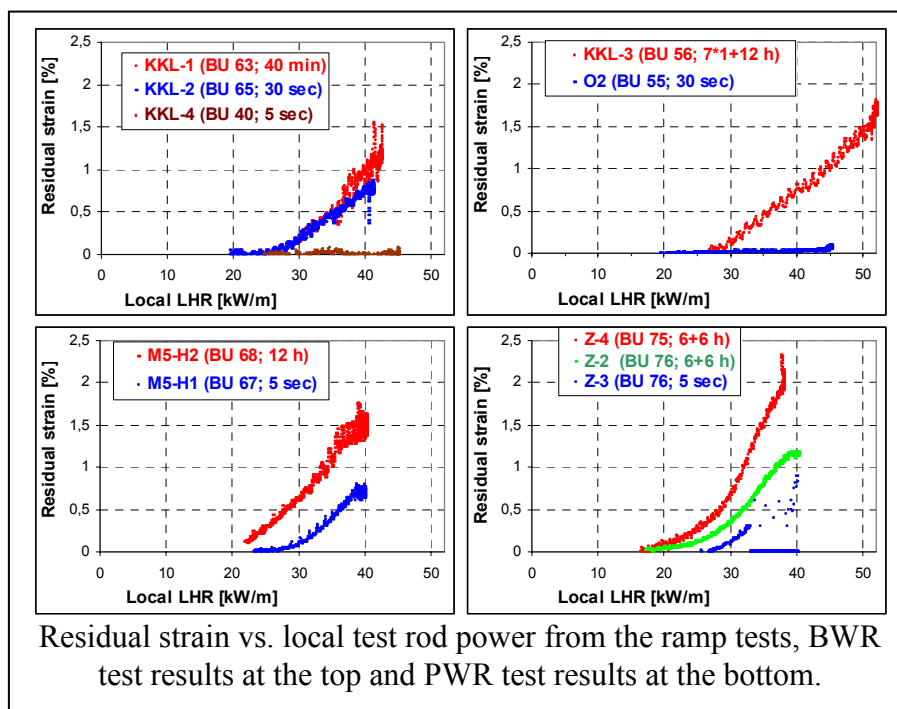
In total 11 ramp rodlets were studied, including PWR and BWR materials and burnup levels between 40 and 75 MWd/kgU. Different ramp types were used for evaluation of strain changes during the holding time. The local diametral residual strain along the cladding was determined by profilometry. The measured residual strain was plotted as functions of local power. Extensive PIE was performed on the tested rods before and after the ramp tests.

These effects and other fuel parameters were further explored by **modeling performed by several SCIP members**. Two separate modeling workshops were arranged, the first was organized by Studsvik and the second by CIEMAT (Spain).

Three different irradiated cladding materials and one unirradiated were tested at temperatures in the range of 310 °C to 400 °C to study the effect of irradiation and strain rate on the **hardening relaxation properties and** to obtain a relationship between stress, strain and time for irradiated claddings with high burnup levels. The results were, among others, used as input data for tuning of the different fuel performance codes used. In Hardening-Relaxation (HRX) testing a cladding sample is internally pressurized, resulting in a diameter increase during the so called hardening phase. After a pre-set diameter change (strain) is obtained, it is kept constant by reducing the pressure during the relaxation phase.

Results Task 0: PCMI - Driving force for fuel failures

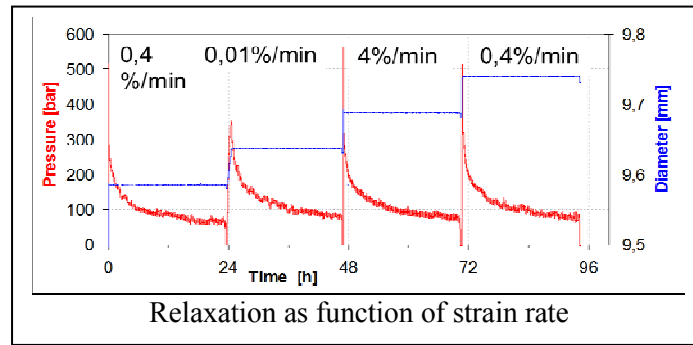
The residual strain results from the ramp tests showed that for low to medium BU levels, there was no measurable residual strain in the BWR fuel tested under typical BWR conditions. On the other hand, at high BU levels, the residual strain increased rapidly with LHR, indicating larger pellet expansion and thus likely larger cladding hoop stresses.



A comparison of short versus long hold times showed that the residual strain increased slightly with holding time in BWR claddings. For the PWR claddings studied, all the rods had high BU. A comparison between short and long hold times in these rods showed that the residual strain increased markedly when the hold time was increased.

The post-irradiation examination (PIE) showed that long hold times lead to higher center porosity and more sintering between the pellets across the interfaces. For the dish filling there is a general trend of lower remaining dish values towards the high power part of the rodlets, reflecting stronger pellet swelling at the higher LHR. The measurements also indicate a clear correlation between the compressed gap, the residual strain and the LHR, while the relocated gap doesn't have any power dependence.

The Hardening-Relaxation mechanical testing showed that relaxation increases with temperature and the unirradiated material has the largest relaxation. Those data was used in the modeling and also used to verify constitutive equations.



The average hydrogen concentration in the 11 rodlets ramp tested was measured and it is clear that the average hydrogen concentration alone is not a sufficient parameter to describe the sensitivity to hydrogen induced failure during a power ramp.

The modeling efforts were attracting large attention from the participants, resulting in several voluntary contributions and the results showed good agreement overall. There are areas that may be looked into when looking for potential improvements, such as the gaseous swelling in models and the need for actual material data was noted, both these parameters are important when discussing the stress and strain histories during the ramp tests.

Task 1: PCI, the classic ISCC failure mechanism

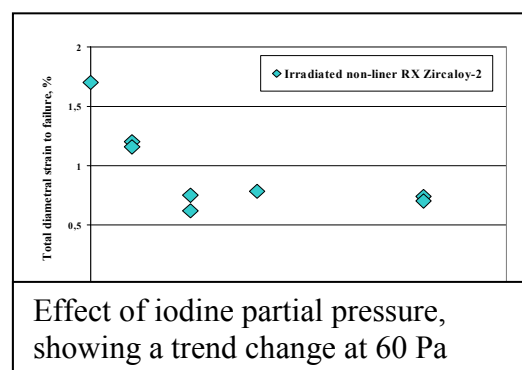
The objectives of Subtask 1 were to establish a reliable out-of-pile method for testing the sensitivity of irradiated claddings to PCI, determine and, if possible, quantify the critical parameters for PCI failures.

An expanding mandrel type testing test technique that can assess the sensitivity to iodine induced PCI (ISCC) of irradiated cladding has been developed. The design was based on a seminar that was held at the beginning of SCIP to present the past experience using different test methods.

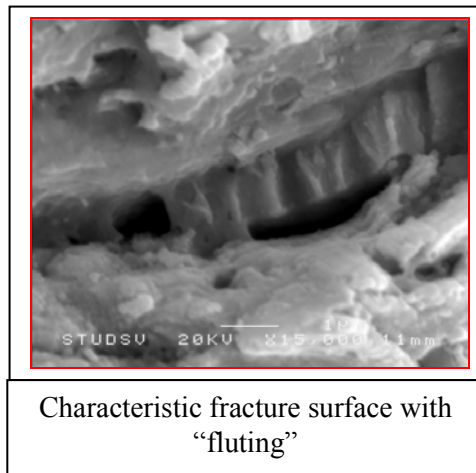
The pellet is simulated by a ceramic insert and the iodine is introduced into the test chamber by the usage of a carrier gas, allowing a controlled partial pressure of iodine. The work focused primarily on knowledge transfer from previous PCI studies and building and qualification of a mandrel type test technique to study ISCC of irradiated fuel cladding. The equipment was used to perform parameter studies on irradiated fuel cladding and to compare PIE of ramp tested rods that failed by PCI and mandrel tests of identical fuel cladding. In addition to the subtasks included in the SCIP programme, CEA has performed numerical simulations of the mandrel tests as a voluntary contribution.

Results Task 1: PCI, the classic ISCC failure mechanism

The results from the tests technique showed that ISCC simulated successfully in cold irradiated Zry-2 without liner as and irradiated ZIRLO. The tests confirm the earlier findings pressure of iodine works as an for ISCC and an increase in value does not influence anymore



using the mandrel failures can be worked unirradiated and well as in unirradiated results of the parameter that 60 Pa partial infinite supply of iodine pressure beyond this the ISCC behavior.



Characteristic fracture surface with
“fluting”

The mandrel tested samples have low strain to failure as well as typical ISCC features on the fracture surface such as fluting. This is consistent with known characteristics of PCI failures and indicates that the mandrel test method developed in SCIP seems to be representative of PCI cladding failures. A general trend of increased strain to failure occurs as the test temperature is increased from 320 to 400 °C.

The new expanding mandrel technique is a promising method presenting measurements on-line, which makes attempts to quantify stress/strain time histories possible and it will be used also in SCIP II.

Tasks 2 and 3: Hydrogen induced failures

The **main objective** of tasks 2 and 3 was to identify and quantify the critical conditions under which hydrogen induced failures, Hydrogen Embrittlement (HE) and Delayed Hydride Cracking (DHC), may occur in BWR and PWR claddings during normal operation and anticipated transients. A secondary objective was to develop a combined approach to study hydrogen induced failures that includes mechanical testing, ramp testing and modeling. A long-term goal is to improve simulations of hydrogen induced failures during power ramps, to such an extent that the sensitivity to this type of failures can be predicted based on operational conditions and material properties and thus can be modeled.

The **objective of the HE studies** was to establish an understanding of hydrogen assisted crack initiation in zirconium based cladding materials and to model/establish critical hydride parameters.

The **objective of the DHC studies** was to establish an understanding of hydrogen assisted crack propagation in zirconium based cladding materials and to establish the critical parameters under which DHC can be the failure mechanism. A second objective was to develop a model of the DHC failure mechanism and study/establish some critical input parameters, such as hydrogen diffusion coefficient and stress fields in clad tubes with hydrides.

A **workshop** was held to wrap up tasks 2 and 3 of the SCIP programme by summarizing key findings and compare the results with other research programs.

The role of hydrogen induced failure mechanisms on the cladding integrity was studied by three different methods; a) in-pile ramp testing, b) out-of-pile mechanical testing and c) modeling of hydrogen induced failures. These methods complement each other and were accordingly all used. While the actual operating conditions in the reactor are simulated in the ramp tests, mechanical testing allows for more controlled parametric studies. Although mechanical testing in combination with ramp testing to some

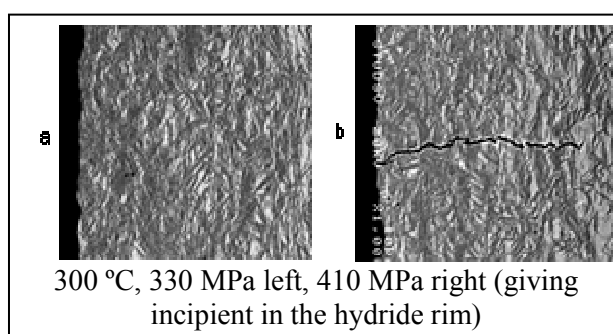
extent can predict in-pile failures they cannot simulate all scenarios. In order to gain a more comprehensive foundation for predicting cladding failures, modeling of the hydrogen induced failure mechanisms was used as a complement to mechanical testing.

The subtasks within these two tasks can be divided into the following areas: Parametric studies on crack initiation in hydrides (HE). Parametric studies on crack propagation by DHC. Development of new test techniques. Modeling of hydrogen induced failures. PIE of selected rodlets ramp tested within Task 0. Basic studies to quantify less known parameters. Knowledge transfer of previous studies on H induced failures (extensive workshop with world-leading experts)

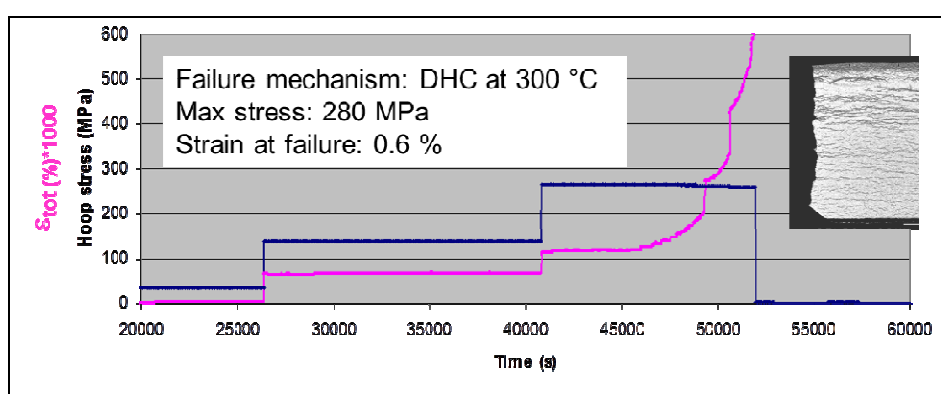
Results Tasks 2 and 3: Hydrogen induced failures

It was shown that in order for HE to occur as a primary failure under operating conditions, a very high density of hydrides is required. These hydride density levels may be reached locally at the outer surface of high burnup rods. In these rods incipient cracks may form in the dense hydride rim at the outer surface at stresses well below the yield stress of the cladding alloy, even at operating temperatures.

A PCMI caused failure may thus be triggered by hydride rim cracking, as a high burnup rod hydride layer may crack, leading to local high stress at the tip of the crack, causing propagation of the crack through the cladding.



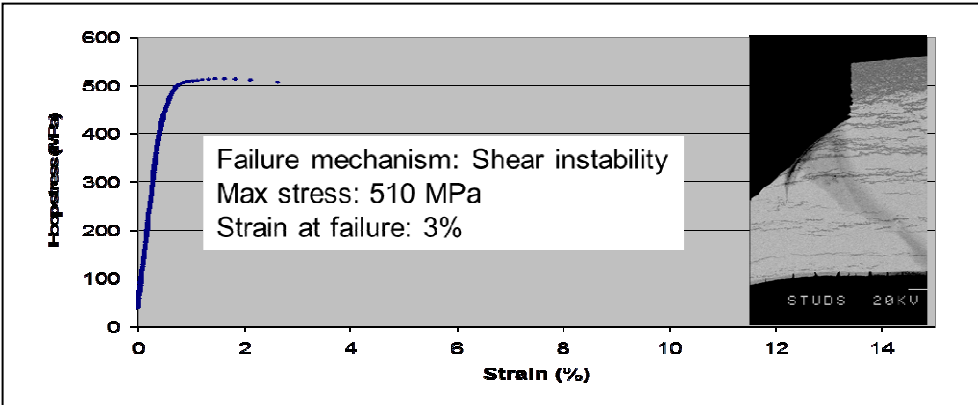
The critical parameters for DHC were quantified and the results confirm that there is an upper temperature limit above which DHC does not operate in the zirconium alloys tested. This is most probably one important contributing factor to why DHC failures have not been documented in PWR reactors.



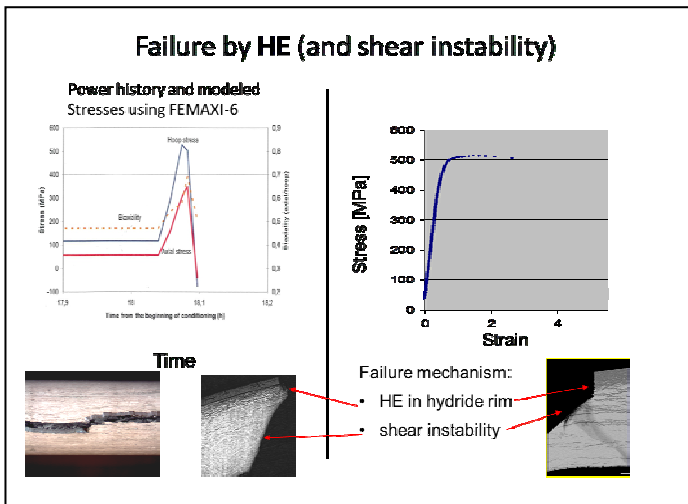
Tests performed on medium to high burnup Zry-2 claddings showed that DHC can operate in these alloys at BWR temperatures. Parametric studies showed that DHC may operate at hydrogen concentrations down to the solubility limit of hydride formation. However, the studies also indicate that in order for DHC

to initiate as a primary failure in claddings with low hydrogen concentrations, high hoop stresses have to be applied.

The mechanical parameter studies confirm that different loading (or power) history triggers different H induced failures; DHC is suppressed during short ramp tests, but can occur at quite low load levels if the hold-time in a loading step is sufficient long (30-60 min). Incipient crack formation by HE occurs



instantaneously at low load levels. However, stresses well above the yield stress are required for the incipient cracks to lead to through wall cladding failure by shear instability,



The out-of-pile mechanical testing showed very good agreement with the in pile testing. In identical fuel rods the same failure mechanisms were triggered under similar test conditions.

At BWR operating temperatures and below, it was observed that several hydrogen enhanced failure mechanisms can coexist. A model has been developed in order to combine different types of hydrogen induced failures. The model was used to simulate H induced failures of samples tested by means of Ring Tensile Testing and Pin Loading Testing. The results show fairly good agreement between the model and the

mechanical testing.

SCIP finished in July 2009 and all SCIP members participate also in the ongoing continuation, the SCIP II project, focusing on the source of the PCMI driving force, the pellet and its behavior, including doped pellets. The SCIP II budget (slightly larger than SCIP) is about 7.500.000 Euro.