Status Update on the SCIP-IV Program in 2020

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology

Oak Ridge National Laboratory
Bruce Bevard

September 30, 2020
M4SF-20OR010201051
ORNL/SPR-2020/1752

SPR-2020/1752

Reactor & Nuclear Systems Division

STATUS UPDATE ON THE SCIP-IV PROGRAM IN 2020

Bruce B. Bevard

September 2020

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

ACRONYMS

ANL	Argonne National Laboratory
DOE	US Department of Energy
EPRI	Electric Power Research Institute
HBU	high burnup
LOCA	loss-of-coolant accident
LWR	light water reactor
MOX	mixed oxide
NE	US DOE Office of Nuclear Energy
NEA	Nuclear Energy Agency
NRC	US Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
PCI	pellet-clad interaction
PNNL	Pacific Northwest National Laboratory
R&D	research and development
SCIP	Studsvik Clad Integrity Program
SFWD	Spent Fuel and Waste Disposition
SFWST	Spent Fuel and Waste Science and Technology
SNF	spent nuclear fuel
SNL	Sandia National Laboratories

ABSTRACT

Phase 1 of the Studsvik Cladding Integrity Project (SCIP) was launched in 2004. It was a 5-year Organisation for Economic Co-operation and Development (OECD) / Nuclear Energy Agency (NEA) joint project operated by Studsvik with about 30 participating organizations, including regulatory bodies, research institutions, utilities, and fuel suppliers from 13 different countries. The initial SCIP program focus was directed toward studying basic phenomena of fuel rod failures driven by pellet cladding mechanical interaction to get a better understanding of fundamental failure mechanisms.

SCIP IV is a continuation of the SCIP programs and is planned to be another five-year project that started in July 2019. It is organized and managed in a manner similar to the earlier SCIP programs, including both a technical group and a management board. The work of SCIP-IV includes significant research into issues related to the back end of the fuel cycle, including spent nuclear fuel (SNF) storage and transportation issues.

Initially, 11 subtasks were proposed for the SCIP-IV program. Four subtasks aim at studying fuel and cladding performance issues related to interim storage. Five subtasks represent a continuation and extension of work performed in SCIP III to investigate loss-of-coolant accident (LOCA) issues. Another task related to pellet-clad interactions (PCIs) is also a continuation and extension of work performed in SCIP III, which included modeling efforts for planning and interpretation of experiments in a dedicated task.

1. INTRODUCTION

The Office of Spent Fuel and Waste Disposition (SFWD) within the US Department of Energy (DOE) Office of Nuclear Energy (NE) established the Spent Fuel and Waste Science and Technology (SFWST) campaign to conduct research and development (R&D) activities related to the storage, transportation, and disposal of light water reactor (LWR) spent nuclear fuel (SNF) and high-level radioactive waste. The SFWST program was created within SFWD to address issues of extended or long-term SNF storage and transportation. Some near-term objectives of SFWST are to use a science-based, engineering-driven approach to:

- Support the enhancement of the technical bases for the continued safe and secure dry storage of SNF for extended periods
- Support the enhancement of the technical bases for retrieving SNF after extended dry storage
- Support the enhancement of the technical bases for transporting high burnup (HBU) and low burnup fuel, as well as transporting HBU fuel after dry storage

This R&D effort includes research into the current state of knowledge with respect to SNF degradation, dry storage designs, the regulatory and operational loadings imposed on these structures, and environmental conditions that may affect the degradation processes and resultant integrity of the SNF. This effort has led to identification of gaps in the knowledge base that have been prioritized and ranked, and experimental work is underway in the DOE-NE High Burnup Spent Fuel Data Project to close the priority gaps.

International cooperation can reduce DOE's overall cost for performing experiments to collect the data necessary to close the identified knowledge gaps. The NEA/OECD SCIP-IV program is one such collaboration. SCIP IV started in July 2019 as a continuation of three earlier 5-year SCIP programs and is planned to be a five-year project. It is organized and managed in a manner similar to the earlier SCIP programs, including a technical committee that reviews experimental results and recommends changes to the experimental test program, along with a management board that must approve any changes. Unlike the earlier SCIP programs, SCIP-IV includes significant research into issues related to the back end of the fuel cycle, including SNF storage and transportation issues.

Initially, 11 subtasks were proposed for the SCIP-IV program. Four subtasks are focused on studying fuel and cladding performance issues related to interim storage. Five subtasks represent a continuation and extension of work performed in SCIP III to investigate LOCA issues. Another task related to PCIs is also a continuation and extension of work performed in SCIP III, which included modeling efforts for planning and interpretation of experiments in a dedicated task.

Data gained from these activities will contribute to a technical basis for the safe storage, transportation, and disposal of SNF by quantifying the mechanical properties of different cladding materials during different burn-up and temperature conditions.

This work aligns with the Gap Analysis to Support Extended Storage and Transportation of Spent Nuclear Fuel (SFWD-SFWST-2017-000005, Rev. 1).

2. WORK PLANNED FOR SCIP-IV

The initial (draft) test plan for SCIP-IV was provided to the program members in 2019, comments were discussed, and modifications to the test plan are ongoing. The initial test plan proposed is outlined below:

2.1 TASK 1 – BACK END

2.1.1 Subtask 1.1 – Creep and hydride reorientation of fuel rods under simulated dry storage conditions

Whereas many creep and hydride reorientation tests of unirradiated cladding have been performed, hardly any data are available on the thermal creep properties of irradiated fuel rods with fuel pellets inside. In HBU fuel rods, fuel-cladding bonding could restrict cladding creep out. In addition to the effects on creep behavior, bonding might also affect hydride reorientation behavior in the cladding, leading to local stress concentrations favoring local hydride reorientation, and creating potential spots vulnerable to crack initiation and propagation under long-term dry storage conditions.

Possible effects due to fuel-cladding bonding in HBU fuel rods will be investigated. Creep properties of rod segments with fuel inside will be compared to defueled cladding properties. Potential hydride reorientation will be assessed, and mechanical properties of the cladding before and after creep testing will be determined.

2.1.2 Subtask 1.2 – Hydride reorientation

During back-end handling and dry storage, fuel cladding temperatures will be high enough to dissolve hydride precipitates back into solid solution. When temperature drops later on, hydrogen will be precipitated again. If the cladding is under high enough hoop stress, then the precipitated hydrides will be oriented in the radial direction, which impacts ductile-to-brittle transition behavior of the cladding material of concern. The conditions and mechanism for hydride reorientation in irradiated cladding material will be determined in order to predict both the hydride reorientation and the ductile-to-brittle transition behavior of the material based on current understanding of these parameters.

2.1.3 Subtask 1.3 – Spent fuel rods in transport and handling operations and in accident scenarios

Independent from the back-end concept, fuel assemblies are handled, loaded into transport casks, and unloaded or stored in dry-storage casks when they are removed from the onsite spent fuel pool. A very large number of transports have been performed successfully worldwide. Only special transportation conditions or accident situations present a substantial need to verify SNF behavior and suitability for further storage. This subtask will concentrate on three areas of concern. It aims at generating valuable experimental data on the mechanical response of irradiated fuel rods under transport accident conditions. The data will support analytical models for regulatory accident evaluation. In addition, the data will also be useful for seismic and vibratory evaluations. In order to support cask containment analysis and the definition of source terms for accident scenarios, the particulates which might be released from HBU fuel rods due to impact events will be characterized. Finally, the strength of weak or slightly damaged fuel rods under transportation and handling operations will be investigated. The aim is to verify that weak or slightly damaged rods will not degrade or jeopardize cask safety functions during transportation and storage.

2.1.4 Subtask 1.4 – Failed fuel

In most countries, no standard procedures have yet been established to take care of failed fuel for interim storage and final disposal. For safe long-term stabilization of failed fuel, the radiological confinement must be restored, and the geometry and environment must be controlled and stable.

Different concepts to encapsulate damaged and failed fuel rods fall into two categories: canning in-pool or conditioning and encapsulation at a hot cell. In this context, drying failed fuel is essential to avoid gas generation by radiolysis of residual water and moisture. The presence of oxygen and hydrogen gas could have undesirable consequences, such as oxidation of the fuel, hydriding of the cladding, corrosion, and pressure build-up. Whereas standards have been established for drying of intact spent fuel in dry storage casks, for failed fuel, these standard drying procedures may not be sufficient to guarantee the required moisture level for encapsulation. Therefore, test methods to measure moisture content must be developed and validated to prove that the criteria on moisture content can be met. Furthermore, available drying procedures must be evaluated for failed fuel and possibly optimized. Within this subtask, experimental data on the issue of safe encapsulation and storage of failed fuel rods will be generated using established characterization methods and assessment of residual water.

2.2 TASK 2 – LOSS-OF-COOLANT ACCIDENTS

2.2.1 Subtask 2.1 – Microstructure related to fuel fragmentation

The existence of a burnup threshold for fuel fragmentation in LOCA scenarios has been a key question in several studies and research efforts. As the experimental evidence grows, it seems that HBU is only one of several factors determining the susceptibility of the fuel to fragmentation. Several hypotheses have been brought forward to explain this behavior, such as effects of the SNF’s power history inducing residual stresses in the pellet, repartitioning of the fission gas inventory to closed grain boundary networks, or bubble populations that weaken the integrity of the fuel under a LOCA event. Recent results from SCIP III have identified some potentially very important effects related to the development of the fuel microstructure in the course of fuel operation. To study the impact of these phenomena further, it is proposed to (1) continue the advanced microscopy examinations performed in SCIP III on fuels with HBU that fragment to a large extent in LOCA-like conditions, and (2) to study HBU fuel that appears resistant to fine fragmentation.

2.2.2 Subtask 2.2 – Fuel fragmentation, relocation, and dispersal in nonstandard fuel

In SCIP III, investigations focused on the performance of *standard fuel*"—that is, UO_2 fuel with relatively small grains—whereas use of large-grain fuel with dopants or additives has become more and more common. Moreover, the microstructure of mixed oxide (MOX) and gadolinia fuel might also develop differently during reactor operation compared to standard fuel. Work to be performed under this subtask aims at extending the database and understanding of fuel fragmentation, relocation, and dispersal of fuel types that have not yet been investigated within SCIP III or elsewhere. The data will support estimates of fuel dispersal in LOCA safety assessments carried out by utilities and regulators, as well as refinement and extension of fuel fragmentation models to be incorporated in fuel performance and transient codes.

2.2.3 Subtask 2.3 – Separate effects tests

Tests in SCIP III have indicated that for fuels susceptible to fine fragmentation, critical parameters may be (1) the temperature ramp rate and (2) the magnitude of the depressurization transient upon burst. The possibility to control temperature ramp rates was rather limited in SCIP III heating tests. Therefore, construction of a new furnace is proposed to better control the temperature ramp rate in tests of similar size instead of continuing with the existing heating test apparatus, which only allows for testing a few pellets worth of material. The equipment will be made compatible with a new depressurization rig to allow for simulating the burst event with a high degree of control, including an expansion chamber to contain and collect the ejected fuel fragments for further study.

2.2.4 Subtask 2.4 – Transient fission gas release and axial gas communication

During a LOCA, rapid and large changes of temperature may cause transient fission gas release from the fuel by mechanisms such as fuel grain boundary fracture or diffusion and interconnection of fission gas bubbles. Understanding the transient fission gas behavior is important to determine factors such as increase in rod inner pressure, margins to cladding burst, and loss of rod integrity. Knowledge of the transient fission gas release also allows for a more accurate determination of the source term in an accident scenario. To properly assess the effects of transient fission gas release on local pressure, ballooning, and burst, it is important to know the axial gas communication inside the fuel rod. As a continuation of a limited number of tests performed in SCIP III, it is proposed to perform a parametric study of axial gas communication against burnup and temperature. The results will support improving fuel performance code models of gas communication under transient conditions.

2.2.5 Subtask 2.5 – Spent fuel pool LOCA

Loss of coolant in a spent fuel pool with high-temperature oxidation of cladding in an air-steam mixture, as well as transients leading to ballooning and burst of fuel rods, can have severe consequences. Within SCIP III, only two LOCA tests under simulated spent fuel pool conditions were performed. Moreover, the scope of post-test examinations was rather limited. Therefore, additional spent fuel pool LOCA tests covering a broader band of potential conditions will be performed in this subtask. The scope of post-test examinations will be extended to provide additional data to define the fission product source term for this type of event.

2.3 TASK 3 – PELLET-CLADDING INTERACTION

2.3.1 Subtask 3.1 – Data for modeling

Fuel performance codes use different methods and criteria to determine when a PCI failure occurs. One of these codes is based on the cumulative damage index that is defined by means of out-of-pile stress corrosion cracking data. Data for standard Zircaloy-2 and Zircaloy-4 cladding have been available for many years, but little or no data on more modern cladding materials are available. This subtask aims at obtaining stress corrosion cracking time-to-failure data for irradiated cladding tubes of modern materials. The data will also be evaluated, compared to existing data, and put into a form suitable for use in fuel performance codes. Model calculations can then be performed, and the damage predictions with the new dataset can be compared to those based on the old set, and they can also be applied to SCIP ramp tests.

2.3.2 Subtask 3.2 – Microstructure and microchemistry

The importance of chemically active agents for stress corrosion cracking is well recognized, but the mode of action of these species, their way to the location of concern and their distribution at the location, their chemical and physical form, and many other aspects, are still not well understood. SCIP III collaboration with the University of Manchester led to promising results. Within this subtask, the microstructure and microchemistry inside the cracks and at the crack tip of irradiated cladding samples that have experienced stress corrosion cracking will be investigated by means of advanced techniques in collaboration with external partners.

2.4 TASK 4 – MODELING

This task aims at supporting SCIP IV with pre- and post-test modeling calculations of tests and experiments using different codes and models. More specifically, the objectives are to provide input for the design of test matrices and the selection of test parameters, to improve the evaluation and interpretation of experimental results, to extend the basis for the validation of existing models, and to identify model improvements and the data needs for such improvements.

3. DOE COMMENTS PROVIDED ON THE DRAFT TEST PLAN

The DOE team includes Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL). The team provided a number of suggested changes to the draft test plan (technical program) in December 2019. It was decided that further in-depth discussion was needed to better understand the DOE comments and the technical basis behind them. A video meeting was held between the Studsvik technical staff and the US DOE team, as well as representatives of the US Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI), in April 2020. In this meeting the DOE comments to the technical program (section 3 above) were discussed in detail, and changes to a number of the backend experiments were accepted for presentation to the SCIP-IV technical and management boards for approval. In a June 2020 video meeting, these changes were accepted, and the test plan was modified accordingly.

4. MEETINGS

Technical meetings to review the results of the SCIP-IV testing program occur biannually, generally in June and December. The December meeting occurred as planned at the Studsvik facility in Sweden, and the June meeting, which was held by videoconference, was attended by personnel from ORNL, PNNL and ANL. Meeting minutes and presentations from those meetings are program proprietary and cannot be included in this report, but they have been distributed to the approved DOE participants.

The next meeting to review progress is scheduled for December 2020 and is planned to occur by video.

5. OUTSTANDING ISSUES

Joining the SCIP-IV program involves the signing of two separate contracts: a bilateral contract with Studsvik that covers payment for the 5-year program, and a contract with NEA/OECD, signed by all participating parties, that contains the program outline and terms and conditions for program participation. As the DOE representative, ORNL has signed the contact with Studsvik and paid the program fee. The contract with the OECD/NEA is more complex, and the terms and conditions portion contains verbiage on arbitration that is not acceptable to DOE and is in the process of being modified. All other contract issues have been resolved.