Hot Cell Post-Irradiation Examination Techniques Vol. II

Authors

Tahir Mahmood
Pleasanton, CA, USA

Kit Coleman
Deep River, ON, Canada

Ron Adamson
Fremont, CA, USA

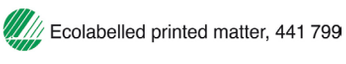
With contributions by
Clément Lemaignan

A.N.T. INTERNATIONAL®

© December 2016

Advanced Nuclear Technology International
Analysvägen 5, SE-435 33 Mölnlycke
Sweden

info@antinternational.com
www.antinternational.com



Disclaimer

The information presented in this report has been compiled and analysed by Advanced Nuclear Technology International Europe AB (ANT International®) and its subcontractors. ANT International has exercised due diligence in this work, but does not warrant the accuracy or completeness of the information. ANT International does not assume any responsibility for any consequences as a result of the use of the information for any party, except a warranty for reasonable technical skill, which is limited to the amount paid for this assignment by each Project programme member.

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Acknowledgements

Authors would like to acknowledge the following individuals and organizations for providing information about their hot cell facilities that made it possible to prepare section 2 of this STR.

- Anna-Maria Alvarez - Studsvik Nuclear AB, Sweden
- Mitchell Meyer - Idaho National Laboratory (INL), USA
- Y. S. Kim, Sangbok Ahn - Korea Atomic Energy Research Institute (KAERI), South Korea
- Elena Zvir- Research Institute of Atomic Reactors (RIAR), Russia
- Margaret McGrath, Håkon Jenssen- Institute for Energy Technology (IFE) – Kjeller, Norway
- Didier Gavillet, Johannes Bertsch - Paul Scherrer Institute (PSI) - Hot Laboratory, Switzerland
- James Miller - Oak Ridge National Laboratory (ORNL), USA
- Kan Sakamoto - Nippon Nuclear Fuel Development Co. (NFD), Japan
- Sheila Rae, Susan Ortner, Amanda Kenway-Jackson - National Nuclear Laboratory (NNL) – Windscale, UK
- Dimitrios Papaioannou, EC, JRC Institute for Trans-uranium Elements (ITU) - Hot Laboratory, Germany
- Didier Gilbon - Laboratory for Studies on Irradiated Fuel (LECI), CEA, Saclay, France
- Didier Gilbon - LECA-STAR Hot Cell Facility, CEA Cadarache, France
- Marin Mincu, Clara Anghel - Institute for Nuclear Research (ICN) - PIE Laboratory, Romania
- Rafael Mizrahi - CELCA hot cell facility, National Atomic Energy Commission (CNEA), Argentina
- Li Guoyun - Hot Laboratory of Nuclear Power Institute of China (NPIC), China
- Zhengqiang Liang - Hot cell facilities, China Institute of Atomic Energy (CIAE), China
- Kristopher Zanotto - GE Hitachi Vallecitos Nuclear Center (VNC), USA
- Jeff Armstrong, David Trudell - Canadian Nuclear Laboratories (CNL), Canada
- Gary Was – University of Michigan Irradiated Materials Testing Laboratory, USA

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Contents

Introduction ..... **VIII**

1 Techniques for microstructural examination **1-1**

1.1 Introduction and summary **1-1**
1.2 Light optical Microscopy **1-7**
1.2.1 Introduction 1-7
1.2.2 Specimen Preparation 1-8
1.2.3 Illumination Techniques 1-8
1.2.4 Color Metallography 1-11
1.2.5 Quantitative Metallography 1-12
1.2.6 Macro Metallography 1-12
1.2.7 Metallography of Irradiated Zirconium Alloy Components 1-12
1.2.7.1 Failed fuel rod investigations 1-13
1.2.7.2 Measurement of cladding corrosion, pellet-clad gap, and clad wall thickness 1-17
1.2.7.3 Characterization of cladding hydride distribution 1-19
1.2.7.4 Grain size measurements 1-22
1.2.7.5 Fuel pellet ceramography 1-23
1.2.7.6 Metallographic examinations of irradiated components other than a fuel rod 1-25
1.3 Scanning electron microscopy or microscope (SEM) **1-27**
1.3.1 Electron Backscatter Diffraction (EBSD) 1-30
1.4 Transmission electron microscopy or microscope (TEM) **1-32**
1.4.1 General 1-32
1.4.2 Zirconium alloys sample preparation techniques 1-35
1.4.2.1 Electrochemical polishing 1-35
1.4.2.2 Ion milling 1-35
1.4.2.3 Focused Ion Beam (FIB) 1-35
1.4.3 Uranium fuel preparation techniques 1-36
1.5 Scanning Transmission Electron Microscopy (STEM) **1-36**
1.6 Electron microprobe analysis (EMPA) or electron probe microanalysis (EPMA) **1-38**
1.7 Secondary Ion Mass Spectroscopy (SIMS) **1-39**
1.8 Advanced techniques **1-41**

2 Hot Cell Post-Irradiation Examination Facilities around the World **2-1**

2.1 Introduction **2-1**
2.2 Summary information on various hot cell PIE facilities **2-2**
2.2.1 Studsvik Nuclear AB, Nykoping, Sweden 2-2
2.2.2 Idaho National Laboratory (INL), Idaho Falls, ID, USA 2-3
2.2.3 Korea Atomic Energy Research Institute (KAERI), Deajeon, Republic of Korea 2-4
2.2.3.1 KAERI Irradiated Materials Examination Facility (IMEF) 2-4
2.2.3.2 KAERI Post-Irradiation Examination Facility (PIEF) 2-6
2.2.4 Research Institute of Atomic Reactors (RIAR), Dimitrovgrad, Russia 2-7
2.2.5 Institute for Energy Technology (IFE) – Kjeller, Norway 2-8
2.2.6 Paul Scherrer Institute (PSI) - Hot Laboratory, Villigen, Switzerland 2-10
2.2.7 Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, USA 2-11
2.2.8 Nippon Nuclear Fuel Development (NFD) Co. Ibaraki-ken, Japan 2-11
2.2.9 National Nuclear Laboratory (NNL) – Windscale, Sellafield, Cumbria, UK 2-13
2.2.10 EC, JRC Institute for Trans-uranium Elements (ITU) - Hot Laboratory, Karlsruhe, Germany 2-14

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

2.2.11 Laboratory for Studies on Irradiated Fuel (LECI), CEA Saclay, France 2-15
2.2.12 LECA-STAR Hot Cell Facility, CEA Cadarache, France 2-17
2.2.13 Institute for Nuclear Research (ICN) - PIE Laboratory, Pitesti, Romania..... 2-18
2.2.14 CELCA hot cell facility, National Atomic Energy Commission (CNEA), Buenos Aires, Argentina 2-19
2.2.15 Hot Laboratory of Nuclear Power Institute of China (NPIC), Jiajiang,Sichuan, Peoples Republic of China 2-20
2.2.16 Hot cell facilities, China Institute of Atomic Energy (CIAE), Tuoli, Beijing, Peoples Republic of China 2-20
2.2.17 GE-Hitachi Vallecitos Nuclear Center (VNC), Vallecitos, CA, USA..... 2-21
2.2.18 Canadian Nuclear Laboratories (CNL), Chalk River, Ontario, Canada..... 2-22
2.2.19 University of Michigan Irradiated Materials Testing Laboratory, Ann Arbor, Michigan, USA 2-23
2.3 Detailed information on various hot cell facilities..... 2-23
2.3.1 Studsvik Nuclear AB, Nykoping, Sweden 2-23
2.3.1.1 Non-destructive examinations..... 2-24
2.3.1.2 Sample preparation 2-25
2.3.1.3 Destructive testing of fuel cladding 2-25
2.3.1.4 The Active Metals Laboratory (defueled cladding)..... 2-28
2.3.1.5 Microscopy facilities 2-30
2.3.1.6 Chemical and radiometric analysis 2-30
2.3.1.7 Customized corrosion testing 2-31
2.3.1.8 The intermediate storage facility 2-31
2.3.1.9 Other resources 2-31
2.3.1.10 Transportation Capability 2-31
2.3.1.11 Disposal and waste treatment..... 2-32
2.3.1.12 Quality..... 2-33
2.3.2 Idaho National Laboratory (INL), Idaho Falls, ID, USA 2-33
2.3.2.1 Hot Fuel Examination Facility 2-33
2.3.2.2 Non-Destructive Examinations 2-34
2.3.2.3 Destructive Examinations 2-37
2.3.2.4 Electron Microscopy Laboratory 2-38
2.3.2.5 Irradiated Materials Characterization Laboratory 2-39
2.3.2.6 Microscopy and Characterization Suite..... 2-39
2.3.2.7 Fuels and Applied Science 2-40
2.3.2.8 Analytical Research Laboratory 2-40
2.3.2.9 Radiochemistry Laboratory 2-41
2.3.3 Korea Atomic Energy Research Institute (KAERI), Deajeon, Republic of Korea2-41
2.3.3.1 Post-Irradiation Examination Facility (PIEF) 2-41
2.3.3.2 Non-destructive examinations..... 2-46
2.3.3.3 Destructive examinations 2-47
2.3.3.4 Electron microscopy..... 2-50
2.3.4 Research Institute of Atomic Reactors (RIAR), Dimitrovgrad, Russia..... 2-51
2.3.4.1 Fuel Transportation 2-51
2.3.4.2 Non-destructive examinations..... 2-52
2.3.4.3 Destructive testing..... 2-58
2.3.4.4 Electron microscopy..... 2-58
2.3.4.5 Mechanical testing 2-60
2.3.5 Institute for Energy Technology (IFE) – Kjeller, Norway 2-60
2.3.5.1 Fuel fabrication laboratory 2-61
2.3.5.2 Neutron radiography laboratory at JEEP II research reactor 2-61

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

2.3.5.3 Concrete and lead shielded hot laboratories 2-62
2.3.5.4 Non-destructive examinations/tests 2-63
2.3.5.5 Destructive PIE and chemical analysis of nuclear fuel 2-63
2.3.5.6 Microstructural analysis 2-64
2.3.5.7 Mechanical testing 2-65
2.3.5.8 Hydride analysis 2-65
2.3.5.9 Thermo-gravimetric analysis 2-66
2.3.5.10 Refabrication & Instrumentation of Irradiated Fuel Rods 2-66
2.3.5.11 Sample preparation 2-67
2.3.6 Paul Scherrer Institute (PSI) - Hot Laboratory, Villigen, Switzerland 2-67
2.3.6.1 Hydrogen charging 2-68
2.3.6.2 Non-destructive examinations 2-68
2.3.6.3 Destructive examinations 2-68
2.3.6.4 Shipping cask information 2-70
2.3.6.5 Access to use the facility 2-70
2.3.7 Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, USA 2-70
2.3.7.1 Transportation of irradiated fuel 2-70
2.3.7.2 Fundamental Characteristics (Nondestructive) Testing 2-71
2.3.7.3 Destructive testing 2-71
2.3.7.4 Irradiated material test equipment 2-72
2.3.7.5 Quality Assurance 2-73
2.3.8 Nippon Nuclear Fuel Development (NFD) Co. Ibaraki-ken, Japan 2-73
2.3.8.1 Concrete cells 2-74
2.3.8.2 Shielded steel cells 2-74
2.3.8.3 Precise measurement laboratory 2-74
2.3.8.4 Microstructure evaluation equipment at NFD 2-75
2.3.8.5 Power Ramp Simulator – Hydrogen Diffusion 2-75
2.3.8.6 Open End Burst – Uniaxial Mechanical Test 2-76
2.3.9 National Nuclear Laboratory (NNL) – Windscale, Sellafield, Cumbria, UK 2-76
2.3.9.1 Windscale facilities 2-76
2.3.9.2 Post-irradiation examination 2-77
2.3.9.3 Decommissioning support 2-78
2.3.10 EC, JRC Institute for Trans-uranium Elements (ITU) - Hot Laboratory, Karlsruhe, Germany 2-78
2.3.10.1 Non-destructive testing 2-80
2.3.10.2 Destructive examinations/testing 2-80
2.3.11 Laboratory for Studies on Irradiated Fuel (LECI), CEA, Saclay, France 2-82
2.3.11.1 Hot cell facility 2-82
2.3.11.2 Authorized materials 2-82
2.3.11.3 Microscopy and irradiation damage studies laboratory 2-82
2.3.11.4 Laboratory for physical and chemical characterizations of irradiated materials 2-83
2.3.11.5 Laboratory for mechanical behavior of irradiated materials 2-83
2.3.12 LECA-STAR Hot Cell Facility, CEA Cadarache, France 2-84
2.3.12.1 Hot cells 2-84
2.3.12.2 Non-destructive examinations 2-85
2.3.12.3 Destructive examinations 2-85
2.3.12.4 Fuel element puncturing 2-85
2.3.12.5 Loops for annealing tests 2-85
2.3.12.6 Fuel rod refabrication 2-86
2.3.12.7 Transportation 2-86

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

2.3.13 Institute for Nuclear Research (ICN) - PIE Laboratory, Pitesti, Romania 2-86
2.3.13.1 Experimental infrastructure 2-87
2.3.14 CELCA hot cell facility, National Atomic Energy Commission (CNEA), Buenos Aires, Argentina 2-88
2.3.15 Hot Laboratory of Nuclear Power Institute of China (NPIC), Jiajiang,Sichuan, Peoples Republic of China 2-89
2.3.15.1 PIE of irradiated fuel elements 2-89
2.3.16 Hot cell facilities, China Institute of Atomic Energy (CIAE), Tuoli, Beijing, China 2-90
2.3.16.1 Description of hot cell facilities 2-90
2.3.16.2 Type of fuel and structural components that can be accepted for PIE: . 2-91
2.3.16.3 Equipment available for PIE of nuclear fuel and structural components:2-91
2.3.16.4 Examples of PIE performed at this facility 2-91
2.3.16.5 Shipping cask information 2-92
2.3.17 GE Vallecitos Nuclear Center (VNC), Vallecitos, CA, USA 2-93
2.3.18 Canadian Nuclear Laboratories (CNL), Chalk River, Ontario, Canada 2-94
2.3.19 University of Michigan Irradiated Materials Testing Laboratory, Ann Arbor, Michigan, USA 2-94
2.3.19.1 Irradiated Materials Complex (IMC) 2-94
2.3.19.2 High Temperature Corrosion Laboratory (HTCL) 2-96
2.3.19.3 Summary of the IML experimental capabilities 2-98

3 Hot Cell Post-Irradiation Examination (PIE) of CANDU Fuel and other Zirconium Alloy Components 3-1

3.1 Introduction 3-1
3.2 CANDU reactor: fuel design and zirconium alloy components 3-1
3.3 Handling irradiated materials at Canadian Nuclear Laboratories (CNL), Chalk River, Ontario, Canada 3-6
3.3.1 The Universal Cells (UC) Facility 3-6
3.3.2 The Fuel & Materials Cells (FMC) Facility 3-7
3.3.3 The NRU spent fuel rod bays 3-7
3.3.4 Analytical Chemistry Laboratories 3-8
3.3.5 Materials Science Laboratories 3-8
3.3.6 Tracking radioactive materials in the hot-cells at CRL 3-8
3.3.7 CNL certifications: 3-9
3.4 Examples of tasks during examinations and how the information is used. 3-9
3.4.1 Visual Inspection 3-9
3.4.2 Dimensional Measurements 3-11
3.4.2.1 Fuel Bundles and Elements 3-11
3.4.2.2 Pressure tubes 3-14
3.4.3 Spectroscopy of Oxide Films 3-17
3.4.4 Hydrogen and Deuterium Analysis 3-19
3.4.5 Gamma scanning. 3-23
3.4.6 Fission Gas Collection and Analysis 3-24
3.4.6.1 Element Puncture and Gas Volume Measurement. 3-24
3.4.6.2 Fission-Gas Analysis. 3-24
3.4.7 Burnup 3-25
3.4.8 Measurement of Mechanical Properties 3-26
3.4.8.1 Tensile testing 3-26
3.4.8.2 Fracture Toughness. 3-27
3.4.8.3 Delayed Hydride Cracking (DHC) 3-29
3.4.8.4 Burst Testing 3-31

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

3.4.9 Microstructural Characterization 3-32
3.5 Summary 3-33
References
Nomenclature
Unit Conversion

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Introduction

Maintaining and improving fuel reliability requires an understanding of the behavior of fuel and materials as related to in-reactor conditions and the mechanisms that have been observed to cause fuel failures. A key factor in improving fuel reliability is the identification of the cause or causes of failure. Such information, in turn, requires the examination and analysis of irradiated fuel (including bundle hardware) at reactor sites (poolside examinations), in hot cells and in other related laboratories. Thus, to make progress toward ultra-high reliability fuel and to reduce the potential for fuel failure, it is imperative to examine both failed and non-failed (reference) fuel.

Post-irradiation examinations (PIE) provide fuel vendors and nuclear utilities with data on how newly developed or established materials withstand normal operating conditions in new environments. Post-irradiation examinations are largely carried out at a Hot Cell Laboratory where irradiated fuel rods and other bundle hardware can be received, handled, examined, and tested. The investigation results provide information for fuel improvement and, thereby, can potentially enhance operating efficiency and reliability. The pool-side and hot cell post-irradiation examination techniques used for LWR fuel and bundle hardware have already been presented in the ZIRAT19 STR titled “Hot Cell Post-Irradiation Examination Techniques for Light Water Reactor Fuels”.

Microstructure plays a central role for the efficient use of zirconium alloys during service in nuclear reactors. The in-reactor performance of components made from zirconium alloys depends on the environment – neutron flux, high temperature and water chemistry – and the properties of the metal – corrosion resistance, mechanical strength, and ductility. These properties are controlled by the microstructure of the alloy. Microstructure describes the crystal phases present, their spatial and orientation distributions and their defect structure. The initial microstructure is determined by the alloy composition and the various working processes and heat-treatments required to fabricate the component and meet various specifications. During service the microstructure is modified by interactions with neutrons and water. It is, therefore, important to investigate the microstructure of irradiated components [Garzarolli, Adamson, and Coleman, 2015]. Various microstructural examination techniques from LOM to STEM and more advanced and specialized techniques are used for this purpose. Section 1 of this STR discusses these techniques along with real world examples of in-reactor microstructural changes and impact on material behavior.

The number of countries with nuclear power programs is growing, while the number of hot cells has diminished during the last decades. This creates problems with post-irradiation examination (PIE) for fuel surveillance, safety control, and nuclear materials studies, including the development of new radiation resistant materials for advanced and innovative nuclear applications. It highlights the need for more efficient use of existing PIE facilities relying on wider international exchange of information about their capabilities.

A number of hot cell facilities exist in various countries around the world. Each of these facilities has its specific strengths and limitations. Section 2 of this STR provides information on PIE capabilities of some of the major hot cell facilities. This information will be useful for utility engineers and engineering laboratories when they need to have PIE performed on failed nuclear fuel or other components.

Section 3 of this STR provides an overview of the status of post-irradiation examination (PIE) and inspection techniques for nuclear fuel and other zirconium alloy components used in CANDU reactors and their applications for analysis of materials behavior in a CANDU reactor core. Emphasis has been given to advanced non-destructive and destructive PIE techniques applied to fuel rods and bundle hardware with examples in the form of case studies.

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

1 Techniques for microstructural examination

1.1 Introduction and summary

The basics of the hot cell techniques used to examine irradiated or unirradiated components include:

1) Optical (or light) microscopy (OM) – best used on flat surfaces, usually highly polished and sometimes etched. Good for revealing surface microstructure such as grain boundaries, second phase precipitates (SPPs), inclusions, etc. Best results for magnification between 25 and 2000.

2) Scanning Electron Microscopy (SEM) – best used for structure or topography of a surface. Little specimen preparation is required, except sample size must be such to fit in the vacuum chamber of the SEM. Depth of focus is high. Good for examining fracture characteristics of a metal. Best results for magnifications between 20-20K. Modifications available for other uses such as surface chemistry or grain orientation.

3) Transmission electron microscopy (TEM) – multiple uses, but frequently for imaging internal microstructure and chemistry of materials. Extensive specimen preparation requiring small disks (3 mm diameter by several hundred nm thick). Good for examining and quantifying grain boundaries, dislocations, cavities, SPPs, etc. Routinely used at magnifications between 2K-200K, but newer instruments reach resolutions near atomic size. Used in the scanning transmission mode (STEM) to determine local chemical/elemental composition.

4) Electron probe microanalysis (EPMA) – analytical technique used to quantify the chemical/elemental composition of small areas of a specimen. X-rays generated near the specimen surface are analysed to determine concentrations of any element (except H, He and Li). X-ray maps are useful for shaving elemental distribution. Volume examined is on the order of 5 μm^3. Used in scanning mode, areas of 100 µm x 100 µm can be probed.

   Table 1-1: and Table 1-2 give summarized information on various techniques for analyses of microstructure. (This information was authored by Dr. C. Lemaignan and was reported in [Garzarolli et al, 2015] and in even more detail in ZIRAT16 Annual Report, Lemaignan in [Adamson et al, 2011].)

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Table 1-1: Comparison of different techniques used in alloy microstructure analysis, C. Lemaignan in [Adamson et al, 2011].

Technique	Aim	Samples	Type of information	Operational aspects	Potential limitations
Chemistry					
SIMS Secondary Ion Mass Spectrometry	In depth profile and surface composition of atoms and isotopes	Limited preparation. Sample size ~ cm^2. Analysis depth up to 2 µm. Deeper analysis on tapered sections.	Time evolution of the different isotopes (e/m separation) versus erosion time. Resolution: ~ µm in location, ~ 5 nm in depth, decreasing with erosion depth. Very high dynamics: 10^5 in concentration differences: impurity detection, segregations.	Rather expensive equipment, not present in all the metallurgy labs. Several services available on commercial basis. Few hours per depth profile.	Light elements (H, He) may be contamination from vacuum chamber. Depth limitations due to erosion time and roughening of the erosion crater. Request to convert time in depth (erosion rates?).
3D atom probe	Exact chemistry and location of all the atoms in a given (very small) volume.	Very sharp needle. (radius < 100 nm, length ~ 5 mm) prepared by electro-polishing or focused ion beam (FIB) difficult and critical. Need to be conductive material.	Within the volume analysed (10*10*100 nm max.), location and isotope description of all the atoms (e/m separation).	Only a few pieces of equipment per continent. The experiments have to be performed by the teams having such equipment.	Vacuum chamber light elements (H, He) contamination. Collection of the atoms: missing atom ratio unknown. The area analysed may not be representative of the sample. Very large amount of data. Would need procedures for data reduction.
Nuclear microprobe	Determine in depth the concentration of given isotopes, having very specific nuclear reactions.	No preparation. Size: a few cm^2. Possibility to analyse radioactive materials in dedicated installations.	Depth concentration of a given isotope, which is very specific for a nuclear reaction occurring with high-energy incident ion beam.	Only a few installations worldwide! Complex extraction of the physics out of the raw data (straggling, multiple reaction, variation of interaction cross sections with energy). Requires an efficient support from the guest lab.	Only a limited set of reaction of interest and therefore of profiles to be obtained. Difficult access to the equipment: request for proposal, travel to the facility, need of a strong scientific support from the local staff.
EXAFS/XANES X-ray Absorption Fine Structure/X-ray Absorption Near Edge Spectroscopy	Describe the environment of all the atoms of a given species under the X-ray beam.	Has to be thin enough for the beam to pass through, or use florescence operation. Depth of analysis below 10 µm.	Raw data is the transmittance of the sample versus X-ray energy. Interpretation of these results in term of local chemistry is not unequivocal. Will analyse all the atoms of the same species. Not phase or gradient separation, only integral or averaged behaviour.	Most of the experiments performed on synchrotron facilities: Formal request of beam times. Many samples can be tested in a few minutes. Excellent support of these installations allows correct interpretation of the results.	Cannot be used without clear expectation of what could be the results. Hypothesis of the suspected environment have to be limited, and a selection will be possible. If configuration is too open, nothing good will come out.
					ANT International, 2011

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Table 1-1: Comparison of different techniques used in alloy microstructure analysis. Cont'd.

Technique	Aim	Samples	Type of information	Operational aspects	Potential limitations
Chemistry					
Diffraction X-ray	Interatomic distances and crystallographic information. Phase identification.	No limitation. Analysis performed on planar surface, or powders for ceramics. Powerful beams can be used in transmission through about 2 mm.	Intensity vs. diffraction distances. Has to be converted in crystallographic description: cell structure, texture, stresses.	Standard equipment available in any metallurgy laboratory. A few hours per sample. Advance measurements with synchrotron limited availability, but much faster.	Penetration depth below 10 µm (except with synchrotron). Calibration procedures have to be done rigorously.
Diffraction neutrons	Same as above	No preparation. Analysis on the bulk of the sample (a few mm^3) Analyse can be performed on minor phases (<1 vol.%)	Same as above, but in bulk.	Request of a neutron beam (pool reactor, spallation source). Long exposition times (hours to days). Specific elements may inhibit the possibilities (H: diffusion, or B: absorption).	Difficult access to the equipment: request for proposal, travel to the facility, but high local scientific support.
TEM **Transmission electron Microscopy**	Imaging of the microstructure at high magnification. Local chemistry and crystallography at the same scale.	Disk (Ø 3 mm, 0.1 µm for electron transparency) Not too difficult for bulk alloy samples (electrochemical thinning). Difficult, but very valuable samples by FIB preparation.	High contrast on the microstructure: grain size and shape, crystallography, orientation, local element concentrations. Resolution near atomic size. Usually combination of the three techniques detailed below.	Very common equipment. Routinely operated by any material science laboratory. A few hours or days for detailed analysis of a sample.	Numerous artifacts due to sample preparation or examination are known and can be avoided by clever teams.
TEM imaging	Direct observation or the microstructure	Ibid.	Grain shape, defects (dislocations, cavities). Details of the interfaces. SPPs	The easiest way to look at a thin foil.	Rather easy to operate and interpret at standard magnifications. Only few limitations.
TEM diffraction	Crystallography of the (single and selected) grain analysed.	Ibid. with selection of the e^- beam coming from only one grain.	Image one cut of the reciprocal space of the crystal analysed. By rotation of the sample, complete description. Epitaxy between grains. Discrete texture analysis. Nature of the defects; Burgers' vector of the dislocations.	Skilled operators, trained on the crystallographic systems of interest obtain this type of information easily.	Lower resolution compared to X-ray diffraction.
TEM chemistry (STEM) X-ray Scanning Transmission Microscopy	Chemistry of the atoms under the beam.	Ibid., but selection of the area to be analysed by focusing the beam.	Composition by examination of the X-ray spectrum.	Usually this technique is performed using a STEM mode. Thus it requires a specific equipment on the TEM in addition to the Energy Dispersive X-ray Spectrometer.	Not very sensitive for light elements. Small e^- beam widening along its path in the foil.
TEM chemistry EELS Electron Energy Loss Spectroscopy	Chemistry of all the area under observation.	Same area of observation as for imaging. Multiple grains, synthetic view.	Fast observation of the chemistry in connection with the imaging mode. Global view of the sample. Fast measurements. Difficult below 0.1at%,	Usually this technique is performed using a STEM mode. In addition, it requires a specific equipment for the selection of the electron beam with a given energy loss.	Good sensitivity for light elements, not too much for heavy ones.

ANT International, 2011

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Table 1-1: Comparison of different techniques used in alloy microstructure analysis. Cont'd.

Technique	Aim	Samples	Type of information	Operational aspects	Potential limitations
Chemistry					
SEM Scanning Electron Microscopy	Morphology of a surface: origin of a fracture or structure of the free surface.	No preparation, but in case of insulators: deposition of a thin conductive layer - C or Au. Size 15×15 mm. Chamber size limitation.	3D surface geometry. Resolution down to 3 nm. Also access to composition and crystallography at µm scale. Best use at 200–20k magnification.	Very common equipment. Examinations in a few minutes. Very high depth of field: high interest compared to optical (light) microscope, for non-planar surfaces.	Almost no limitation. Needs vacuum as environment.
SEM imaging	3D surface geometry	Same as above.	Surface contrast with shadow, (secondary electron mode). Atomic number contrast in back scattered electron mode.	Very easy. Observation in a few minutes. Wide range of magnifications, with instantaneous blow-up.	At edges, high emission of secondary electrons.
SEM EBSD Electron Back Scatter Diffraction	Crystallographic orientation of the grains under examination.	Same as above, but usually polished. Highly work-hardened material will not produce valuable data.	Crystal orientation on each point of analysis. Resolution ~ 1 μm^3.	Requires specific equipment on the SEM with associated software. Now frequent. For a normal sample, examination of all the grain orientations in a few hours.	Surface degradation (mechanical polishing, oxidation) would perturb the acquisition of data
SEM chemistry with X-ray emission	Chemistry under the beam.	Same. Analysis performed on the area under the beam (~ 1 μm^3).	Chemistry on each point of analysis. Resolution ~ 1 μm^3. Difficult below 0.2 at%. Possibility of chemical 2D maps, by scanning of the beam.	Rather easy for qualitative acquisitions. Corrections for ZAF nor very easy for wavy surfaces. Several hours for complex analysis.	High background in addition to the characteristic lines, due to complete stopping of the e^- beam. Only averaged composition given over ~1 μm^3. (matrix + precipitates).
					ANT International, 2011

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Table 1-1: Comparison of different techniques used in alloy microstructure analysis. Cont'd.

Technique	Aim	Samples	Type of information	Operational aspects	Potential limitations
Other techniques					
Mössbauer effect	Describe the environment of a given isotope by the modification of the energy of a chosen nuclear transition.	Request of specific sample preparation, with doping in the isotopes of interest (^{57}Fe and ^{119}Sn).	The transmitted intensity versus difference in energy with the transition analysed. Has to be interpreted according to a combination of spectra characteristics of various chemical states of the atom environment.	Dedicated equipment, with a radioactive source. Not very easy to access. Probably limited interest for Zr alloys.	Very few isotopes of interest for Zr alloys: ^{57}Fe and ^{119}Sn. Structural analysis not unequivocal, often questionable results. The samples processed with the selected isotopes may be different from large industrial samples. Restricted to basic understanding.
Raman spectroscopy	Describe the environment of a given isotope by the changes in vibration frequencies.	Flat surface, as for classical optical (light) microscope. Metals and alloys are not concerned due to their opacity to IR photons.	Overall spectrum within a large wavelength range. Phase concentration or structure versus location of analysis or external conditions.	Simple equipment on an optical microscope. Easy operation.	Some phases do not have sharply defined spectra. In the case of external parameter calibration, such as stress level, basic physics may be required in the case of anisotropic materials.
TEP Thermo Electric Power	A change in microstructure is determined by a change in the thermo-electric parameter.	Flat samples, allowing to stabilize a thermal gradient without too much thermal power loss. Restricted to metals and alloys.	Raw data are the TEP coefficients. The changes with experimental parameters point the occurrence of a change in microstructure, without any information on its nature.	Dedicated, but not too complex, equipment. Available in a limited number of labs. A typical measurement would last few minutes.	Any change in microstructure could induce a change in TEP. Additional techniques mandatory to characterize the nature of this change.
Others	Determine a change in microstructure by the change in one physical property.	Various, adjusted to the technique.	The change of the parameter measured, with experimental conditions, points the occurrence of a change in microstructure.	Completely technique dependent. A complex technique, available on-site could be preferred by a given team, compared to another one, simpler, but not local.	The question is always: what could be the different physical mechanisms linking the measurements to the changes in microstructure?

ANT International, 2011

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Table 1-2: Techniques recommended for a given objective, and comments, C. Lemaignan in [Adamson et al, 2011]

Question to be answered		Possible techniques	Comments
Chemistry	Chemical environment of a given atom.	3D atom probe	Very difficult and complex. Representativeness of the area analysed. Very large amount of data acquired. Access rather difficult.
		EXAFS/XANES	Efficient. Access to synchrotron. Not unequivocal analysis.
	Composition profile	SIMS	Not too difficult. Fairly good for light atoms. High dynamics. Interest for low concentrations. Possible on radioactive materials at a few labs.
		Nuclear microprobe	Very difficult and specific. Should be limited to very well focused studies. Access difficult.
		SEM with X-ray profile	Easy. Not very efficient for light atoms. Good above 1 at.%.
	Composition of a phase	TEM	A standard procedure. Need sample preparation. Easy combination with TEM diffraction.
		SEM with X-ray	Very simple. Limited to 1 µm depth, and 1 µm in volume resolution.
Crystallography	Crystallography of a given phase	X-ray diffraction	The standard procedure. No need for complex sample preparation.
		TEM diffraction	A simple procedure. Easy combination with TEM for morphology and composition.
		Neutron diffraction	Rather difficult and lengthy in acceptance procedures. Interest for bulk data.
	Orientation of the grains	TEM diffraction	Limited to specific measurements. Gradient in orientation of small grains.
		EBSD	Interesting in understanding mechanisms. Large amount of data to process.
	Texture	X-ray diffraction - texture	Simple, gives averaged information. Surface analysis only. If bulk information required use Synchrotron or neutron diffraction.
Phases present	Nature	X-ray diffraction	The normal procedure. No need for complex sample preparation.
		TEM (diffraction)	A simple procedure. Easy combination with TEM for morphology and composition.
	Volume fraction / grain size/ Morphology of each grain	Optical(light) microscopy	A very efficient technique. Easy and accurate. **Not to be forgotten.**
		SEM	Similar and simple. But the contrast may be difficult to obtain on Zr alloys.
		X-ray diffraction	Also a normal procedure. Need calibration in a few cases. Caution with textured samples.
ANT International, 2011			

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

1.2 Light optical Microscopy

1.2.1 Introduction

Light Optical Microscopy (LOM), also known as Light Microscopy or Metallography, is the study of the microstructure of all types of metallic alloys. It can be more precisely defined as the scientific discipline of observing and determining the structure and spatial distribution of the constituents, inclusions or phases in metallic alloys. Different techniques are used to reveal the microstructural features of metals. Most investigations are carried out with incident light microscopy in bright field mode, but other less common contrasting techniques, like dark field or differential interference contrast (DIC), and the use of colour (tint) etching are expanding the scope of LOM for metallographic applications [Diez, 2013].

Many important macroscopic properties of metallic materials are highly sensitive to the microstructure. Critical mechanical properties, like tensile strength or elongation, as well as other thermal or electrical properties, are directly related to the microstructure. The understanding of the relationship between the microstructure and macroscopic properties plays a key role in the development and manufacture of materials and is the ultimate aim of metallography [Garzarolli et al, 2015].

Metallography, as we know it today, owes much to the contribution of the 19th century scientist Henry Clifton Sorby[1]. His pioneering work with modern manufactured iron and steel in Sheffield (UK) highlighted this intimate bond between the microstructure and macroscopic properties. As he stated towards the end of his life: "In those early days, if a railway accident had occurred and I had suggested that the company should take up a rail and have it examined with the microscope, I would have been looked upon as a fit man to send to an asylum. But that is what is now being done ..."

Together with new developments in microscopy technology and, more recently, with the aid of computing, metallography has been an invaluable tool for the advancement of science and industry over the last hundred years. Some of the earliest correlations between microstructure and macroscopic properties established in metallography using light microscopes include:

- A general increase in yield strength and hardness with decreasing grain size
- Anisotropic mechanical properties with elongated grains and/or preferred grain orientations
- A general tendency of decreased ductility with increasing inclusion content
- A direct influence of inclusion content and distribution on fatigue crack growth rates (metals) and fracture toughness parameters (ceramics)
- The association of failure initiation sites with material discontinuities or microstructural features, such as second-phase particles

By examining and quantifying a material's microstructure, its performance can be better understood. Thus, metallography is used in almost all stages during the lifetime of a component: from the initial materials development to inspection, production, manufacturing process control, and even failure analysis if needed. The principles of metallography help to ensure product reliability.

Metallography has been traditionally described as both a science and an art, and the reason for this statement lies in the fact that experience and intuition are equally important for exposing the true structure of the material without causing significant change or damage, in order to reveal and make measurable the features of interest.

---

[1] **Henry Clifton Sorby** was a pioneer in the application of microscopy techniques to the study of geological and metallic materials, a past president of the Royal Microscopical Society and a founder of The University of Sheffield. 150 years ago, Sorby was the first to use etching with acid to study the microstructure of iron and steel. Using this technique, he was the first to understand that a small but precise quantity of carbon gave steel its strength [1911 Encyclopædia Britannica, Volume 25, Wikipedia].

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

2 Hot Cell Post-Irradiation Examination Facilities around the World

2.1 Introduction

The number of countries with nuclear power programs is growing, while the number of hot cells has diminished during the last decades. This creates problems with post-irradiation examination (PIE) for fuel surveillance, safety control, and nuclear materials studies, including the development of new radiation resistant materials for advanced and innovative nuclear applications. It highlights the need for more efficient use of existing PIE facilities relying on wider international exchange of information about their capabilities.

Post-irradiation examinations are carried out at a Hot Cell Laboratory where irradiated fuel rods and other bundle hardware can be received, handled, examined, and tested. A number of hot cell facilities exist in various countries around the world. Each of these facilities has its specific strengths and limitations. This section of the STR provides information on PIE capabilities of some of the major hot cell facilities. This information is useful for utility engineers and members of engineering laboratories for their needs to have PIE performed on irradiated components. The hot cell facilities, for which information is provided here, include

- Studsvik Nuclear AB, Nykoping, Sweden
- Idaho National Laboratory (INL), Idaho Falls, ID, USA
- Korea Atomic Energy Research Institute (KAERI), Deajeon, Republic of Korea
- Research Institute of Atomic Reactors (RIAR), Dimitrovgrad, Russia
- Institute for Energy Technology (IFE) – Kjeller, Norway
- Paul Scherrer Institute (PSI) - Hot Laboratory, Villigen, Switzerland
- Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, USA
- Nippon Nuclear Fuel Development Co. (NFD), Ibaraki-ken, Japan
- National Nuclear Laboratory (NNL) – Windscale, Sellafield, Cumbria, UK
- EC, JRC Institute for Trans-uranium Elements (ITU) - Hot Laboratory, Karlsruhe, Germany
- Laboratory for Studies on Irradiated Fuel (LECI), CEA, Saclay, France
- LECA-STAR Hot Cell Facility, CEA Cadarache, France
- Institute for Nuclear Research (ICN) - PIE Laboratory, Pitesti, Romania
- CELCA hot cell facility, National Atomic Energy Commission (CNEA), Buenos Aires, Argentina
- Hot Laboratory of Nuclear Power Institute of China (NPIC), Jiajiang,Sichuan, Peoples Republic of China
- Hot cell facilities, China Institute of Atomic Energy (CIAE), Tuoli, Beijing, Peoples Republic of China
- GE Hitachi Vallecitos Nuclear Center (VNC), Vallecitos, CA, USA
- Canadian Nuclear Laboratories (CNL), Chalk River, Ontario, Canada
- University of Michigan Irradiated Materials Testing Laboratory (IMTL), Ann Arbor, Michigan, USA

Section 2.2 provides summary information on hot cell characteristics, irradiated material acceptance criteria, and available examination/test techniques at each of these laboratories. Since each piece of information was not available for each facility, there are some gaps in the information provided here. Section 2.3 provides more detailed information on each of the facilities, equipment, and techniques

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

along with some sample results. More information can be obtained from the cited references and by contacting the facility.

2.2 Summary information on various hot cell PIE facilities

[IAEA, 2012]

Units for gamma activity, in the tables below, are TBq (1 TBq=27 Ci) and all dimensions are in meters.

2.2.1 Studsvik Nuclear AB, Nykoping, Sweden

Available Techniques

Visual Examination	Axial tensile tests
Profilometry	Ring compression tests
Axial gamma scanning	Charpy-V
Non-destructive burnup measurement	CT specimen testing
Eddy current examination	Fatigue testing
Oxide thickness measurement	Pin-loading FT testing
Cladding inside inspection	Creep and hardening relaxation tests
Sample preparation	Mandrel testing for PCI studies
LOCA testing	Light optical microscopy
Sieve analysis	SEM, TEM, STEM, examinations
Four point bend testing	Chemical and radiometric analyses
High temperature annealing	Fuel transport and storage
Hardness testing	Expert consultancy services
Ring tensile tests	Disposal and waste treatment

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

2.2.2 Idaho National Laboratory (INL), Idaho Falls, ID, USA

Cell Characteristics			
Purpose			
Gamma Activity Limit (Concrete)		# of Concrete Cells	8
Gamma Activity Limit (Steel)		# of Steel Cells	0
Gamma Activity Limit (Lead)		# of Lead Cells	0
Cell Atmosphere	Argon and air	Maximum Length of Rod	3.86
Largest Cell Width (m)	9.1	Scheduled Maintenance	…
Largest Cell Length (m)	21.3		
Largest Cell Height (m)	7.6		

Acceptance Information			
Acceptance Type	Rods, fuel assemblies	Acceptance Condition	Dry
Transfer Mode	Vertical		
Maximum Cask Weight (t)	30		
Max. Fissile Enrichment (%)	no limit	Maximum Cask Length (m)	5.2
Failed Rod Acceptance	Yes	Max. Fissile Weight (kg)	10*
Accepted Casks		Protective Tube	Yes
Comment	Nearly any commercial DOT (Department of Transportation–USA) or DOE (Department of Energy–USA) cask can be accepted. Information provided here applies to HFEF, facilities may vary. *10 kg Fissile weight for 22 individual zones of HFEF main hotcell		

Available Techniques

Density
Visual Examination
Gamma Scanning
Rod Length measurement
Profilometry
Other (Bow Examination)
Eddy Current Testing
Neutron Radiography
Other (Gas Assay Sample and Recharge (GASR))
Machining
Tensile Testing
SEM
Other (Metallurgical Analysis)
Other (Coated Particle Sieving And Inspection)
Other (Carbon, Oxygen, Nitrogen Analysis)
Gamma Spectroscopy
ICP Atomic Emission Spectroscopy-DE
Other (Atomic Absorption Analysis)
Thermal Ionisation Mass Spectrometry (TIMS)

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Inductively Coupled Plasma/Mass Spectrometry (ICP/MS)

Other (Gross Alpha/Beta Analysis)

Element analysis (EDAX or WDAX)

Other (Alpha/ Beta spectroscopy)

Other (Gass Mass analysis)

Processing of Isotopes

Thermal Diffusivity

X-ray Diffraction

EPMA

Micro Hardness Testing

Other (Nanoindenter)

Other (Dual Beam Focused Ion Beam (FIB))

Other (Positron Annihilation Spectroscopy (PAS))

Other (Atom probe)

Raman Spectroscopy

TEM

DTA\DTG\DSC

FEGSTEM

Optical Microscopy

2.2.3 Korea Atomic Energy Research Institute (KAERI), Deajeon, Republic of Korea

2.2.3.1 KAERI Irradiated Materials Examination Facility (IMEF)

Cell Characteristics			
Purpose	PIE of fuel assemblies, rods and irradiated materials		
Gamma Activity Limit (Concrete)	37000	# of Concrete Cells	6
Gamma Activity Limit (Steel)	0	# of Steel Cells	0
Gamma Activity Limit (Lead)	1.85	# of Lead Cells	1
Cell Atmosphere	Air	Maximum Length of Rod	1
Largest Cell Width (m)	3	Scheduled Maintenance	Yes
Largest Cell Length (m)	7.08		
Largest Cell Height (m)	6		

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Acceptance Information			
Acceptance Type	Acceptance as either assemblies or rods	Acceptance Condition	Dry & Wet
Transfer Mode	Vertical		
Maximum Cask Weight (t)	30		
Max. Fissile Enrichment (%)	85 Pu(f)/19.75U(f)	Maximum Cask Length (m)	1
Failed Rod Acceptance	Yes	Max. Fissile Weight (kg)	
Accepted Casks		Protective Tube	No
Comment	In case of transportation of PWR rod through the fuel rod door of M1 hot cell, the transfer mode is horizontal.		

Available Techniques

Visual Examination
Length and Diameter
Gamma Scanning
Eddy Current Testing
Oxide Thickness
Rod Puncture
Optical Microscopy
SEM
Image Analysis
EPMA
TEM
Density
Burnup
Thermal Diffusivity
Clad Chemical Composition
Tensile Testing
Clad Creep Testing
Clad Fatigue Testing
Micro Hardness Testing
X-Radiography

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

2.2.3.2 KAERI Post-Irradiation Examination Facility (PIEF)

Cell Characteristics			
Purpose	PIE of fuel assemblies and rods		
Gamma Activity Limit (Concrete)	10000	# of Concrete Cells	4
Gamma Activity Limit (Steel)	0	# of Steel Cells	0
Gamma Activity Limit (Lead)	25	# of Lead Cells	2
Cell Atmosphere	Air	Maximum Length of Rod	4
Largest Cell Width (m)	1.5	Scheduled Maintenance	Yes
Largest Cell Length (m)	3.5		
Largest Cell Height (m)	6.5		

Acceptance Information			
Acceptance Type	Acceptance as either assemblies or rods	Acceptance Condition	Wet
Transfer Mode	Vertical		
Maximum Cask Weight (t)	50		
Max. Fissile Enrichment (%)	5	Maximum Cask Length (m)	4
Failed Rod Acceptance	Yes	Max. Fissile Weight (kg)	
Accepted Casks		Protective Tube	Yes
Comment	Maximum Fissile Enrichment: 5.0 wt % Fissle U and/ or Pu		

Available Techniques

Visual Examination
Length and Diameter
Gamma Scanning
Eddy Current Testing
Oxide Thickness
X-Radiography
Clad-fuel Gap
Rod Puncture
Optical Microscopy
SEM
Element analysis (EDAX or WDAX)
Density
Burnup
Melting Point
Clad Chemical Composition
Micro Gamma Scanning
Hardness Testing
Leak Testing

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

2.2.4 Research Institute of Atomic Reactors (RIAR), Dimitrovgrad, Russia

Cell Characteristics			
Purpose	PIE of fuel assemblies and rods		
Gamma Activity Limit (Concrete)	10000	# of Concrete Cells	64
Gamma Activity Limit (Steel)		# of Steel Cells	
Gamma Activity Limit (Lead)	300	# of Lead Cells	13
Cell Atmosphere	Air	Maximum Length of Rod	4.3
Largest Cell Width (m)	8	Scheduled Maintenance	Yes
Largest Cell Length (m)	6		
Largest Cell Height (m)	8		

Acceptance Information			
Acceptance Type	Rods & Assemblies	Acceptance Condition	Dry & Wet
Transfer Mode	Horizontal & Vertical		
Maximum Cask Weight (t)	50		
Max. Fissile Enrichment (%)	100	Maximum Cask Length (m)	4.3
Failed Rod Acceptance	Yes	Max. Fissile Weight (kg)	125
Accepted Casks		Protective Tube	…
Comment	Purpose: destructive and non destructive PIE of fuel rods, assemblies and control rods. Refabrication of experimental fuel rods. Examination of vessel materials and materials of in-vessel facilities. Tests and researches to provide safety of nuclear power plants.		

Available Techniques

Burnup
Density
SEM
Image Analysis
Thermal Diffusivity
Hydrogen Analysis
Creep Testing
SIMS
Auger Spectroscopy
Specific Heat
Tensile Testing
Length and Diameter
Gamma Scanning
Oxide Thickness
Clad-fuel Gap
Rod Puncture
Visual Examination
Rod Length measurement

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Fuel rod volume
Leak Testing
Fuel Assembly Top Nozzle Spring's Parameters
Spacer Grid Geometrical Parameters
Guide Channel Diameter
Micro Gamma Scanning
Hardness Testing
TEM
Fracture Mechanic Testing
Youngs Modulus
Electric Resistance
Helium Analysis
Dilatometry
Other Mechanical Testing
X-Radiography
Eddy Current Testing
X-ray Diffraction
Optical Microscopy
Charpy Testing

2.2.5 Institute for Energy Technology (IFE) – Kjeller, Norway

Cell Characteristics			
Purpose	Main purpose of the Hot Cell facility is PIE of fuel rods and/or assemblies and structural components from HBWR and JEEP2 in dry condition. Other activities in the Nuclear Fuel Section include UO2-pellet production of standard and experimental fuel.		
Gamma Activity Limit (Concrete)	4000	# of Concrete Cells	3
Gamma Activity Limit (Steel)		# of Steel Cells	0
Gamma Activity Limit (Lead)		# of Lead Cells	5
Cell Atmosphere	Air	Maximum Length of Rod	1.8
Largest Cell Width (m)	3	Scheduled Maintenance	No
Largest Cell Length (m)	6		
Largest Cell Height (m)	4.2		

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Acceptance Information			
Acceptance Type	Fuel rods, assemblies and structural components	Acceptance Condition	Dry
Transfer Mode	Horizontal		
Maximum Cask Weight (t)	10		
Max. Fissile Enrichment (%)	20 %	Maximum Cask Length (m)	4
Failed Rod Acceptance	Yes	Max. Fissile Weight (kg)	80 % of lowest critical mass
Accepted Casks		Protective Tube	Yes
Comment	If the transport container is larger than 10 tons, it has to be repacked at IFE/Halden.		

Available Techniques

Density
Alpha-Beta Autoradiography
Micro Gamma Scanning
Hydrogen Analysis
Tensile Testing
Visual Examination
Eddy Current Testing
Rod Puncture
Optical Microscopy
SEM
Tube Burst Testing
Inner Clad Inspection
O to M Ratio
Micro Hardness Testing
Neutron Radiography
Gamma Scanning
Length and Diameter
Image Analysis

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

3 Hot Cell Post-Irradiation Examination (PIE) of CANDU Fuel and other Zirconium Alloy Components

3.1 Introduction

As with Light Water Reactors (LWR), post-irradiation examination (PIE) plays a vital role in understanding the behaviour of fuel and reactor components in Pressurised Heavy Water Reactors (PHWR), exemplified by **CAN**ada **D**euterium **U**ranium (CANDU) reactors. To place these reactors in context, the main differences between typical LWRs, for example Pressurised Water Reactors (PWRs), and CANDUs are summarised, then the requirements and methods for PIE are described and examples of results are provided. (Note that in the other main LWR, Boiling Water Reactors (BWRs), as the name implies the water is allowed to boil.)

3.2 CANDU reactor: fuel design and zirconium alloy components.

Nuclear power reactors based on fission of uranium have several common requirements:

- **Fuel**: The isotope U-235 provides energy from nuclear fission; as mined, natural uranium contains 0.7% U-235 that is fissionable and 99.3% U-238 that is not immediately fissionable. To increase the probability of fission, the concentration of U-235 can be increased by enrichment. Commercial reactors use uranium in the form of UO_2. Pellets of uranium oxide (UO_2) are protected by cladding or sheathing tubes made from a zirconium alloy to form fuel rods or elements. The rods are arranged into fuel assemblies or bundles in the reactor core.
- **Moderator**: The probability of fission is increased by a factor of about 250 if the initial neutron energy of the fast neutrons, average about 1 MeV, is reduced down to 0.025 eV. This process is called moderation. Now the neutrons are called slow or thermal neutrons. In practice moderators are light water, heavy water or graphite. Light water is more effective than heavy water in slowing neutrons but has a higher neutron absorption cross-section. The moderating ratio, (slowing power/capture cross-section) is about 80 times greater for heavy water than light water, while that of graphite is about 30 times greater than light water.
- **Heat-transfer medium (or coolant)**: Water is circulated through the fuel to extract heat to form steam that drives a turbine and electric generator.
- **Pressure vessel: T**he heat-transport fluid is pressurised to maintain the water as a liquid. It is contained in either a thick steel vessel that holds the reactor core and moderator, or a series of tubes made from a zirconium alloy, penetrating the moderator, that holds the fuel and heat-transport water.

The various types of reactors use these components differently. When heavy water is used as moderator, the fuel may be natural uranium. When the moderator is ordinary, light water, a sustainable nuclear reaction requires the U-235 isotope to be enriched, in practice up to 5%.

Light water is used for both moderator and heat-transport in both PWRs and BWRs. The design comprises a primary heat transport (PHT) circuit in which water flows through the core of the reactor under high pressure within a steel pressure vessel and a secondary circuit in which steam is generated to drive the turbine. The main features of a PWR are depicted schematically in Figure 3-1. A PWR has fuel assemblies of over 200 rods clad with a zirconium alloy, about 3.5 m in length, arranged vertically in the core in an open lattice; a large reactor would contain about 150–250 fuel assemblies. The outer surface of the fuel cladding may be as high as 350°C and the required pressure is about 15 MPa to retain the water as liquid in the reactor core.

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

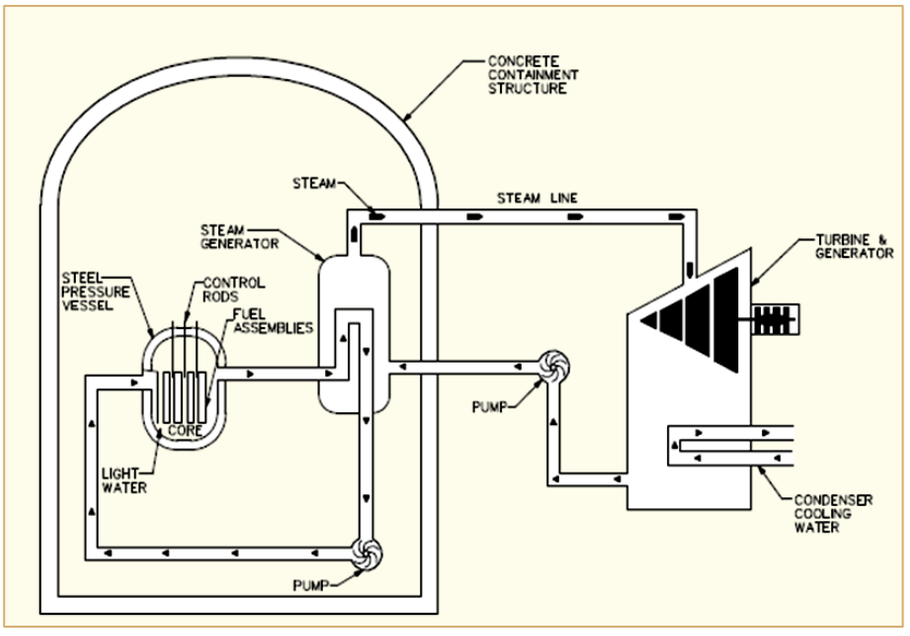


Figure 3-1: Schematic diagram of a PWR.

The main features of a PHWR are depicted schematically in Figure 3-2. In a CANDU reactor the fuel is natural uranium and the moderator and heat-transport fluid are heavy water. The moderator is held at about 70°C in a large tank, called a calandria, penetrated horizontally by up to 480 pairs of concentric tubes forming the fuel channels. The inner tube of the fuel channel, the cold-worked Zr-2.5Nb pressure tube, is about 6 m long, has an inner diameter of 103 mm and a wall thickness of 4 mm. It contains up to 13 fuel bundles and the heat-transport fluid. The outer tube, the Zircaloy-2 calandria tube, is separated from the hot pressure tube by spacers in the form of garter springs. The calandria tube isolates the hot pressure tube from the cool moderator, insulation being provided by filling the annular space between the two tubes with dry CO_2 at atmospheric pressure. The calandria tube has an inner diameter of 130 mm and wall thickness of 1.4 mm. Heat transport is by a flow of heavy water under a pressure up to about 11 MPa with exit temperatures of about 310°C. As in the PWR, the primary coolant generates steam in a secondary circuit to drive the turbines.

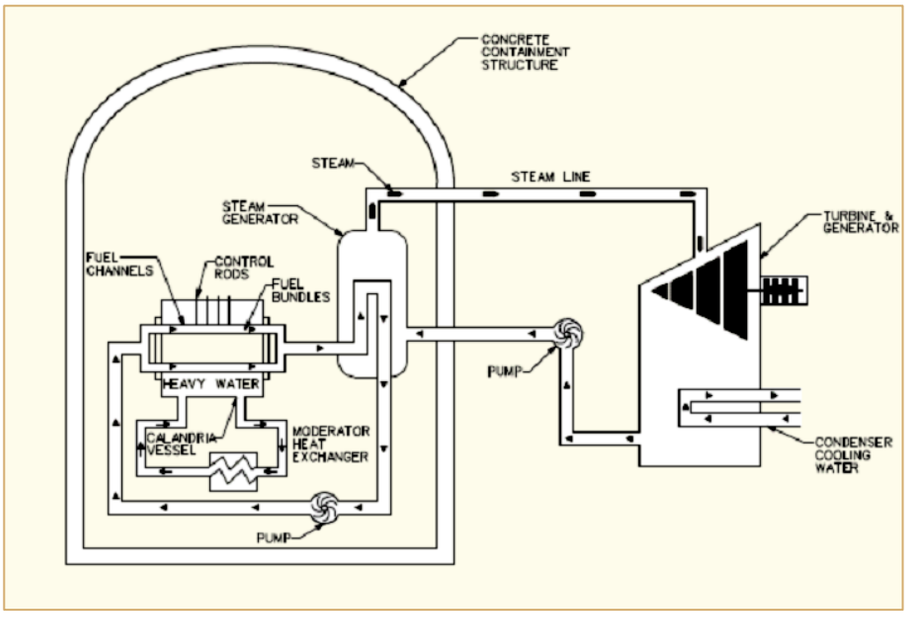


Figure 3-2: A schematic diagram of a PHWR.

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

The pressure tube is attached to the reactor vessel by a rolled joint in a 403 stainless-steel end-fitting, Figure 3-3. One end is free to elongate from thermal expansion and deformation. The tube is biaxially stressed by the pressure of heavy water, in closed end mode, and is also loaded by the weight of the water and fuel leading to sag. The hoop stress in the calandria tube is small and, because it is at a low temperature, it controls the sag of the fuel channel. The calandria tube is attached directly to the reactor vessel; if the pressure tube should rupture, the calandria tube would be pressurized in fixed end mode.

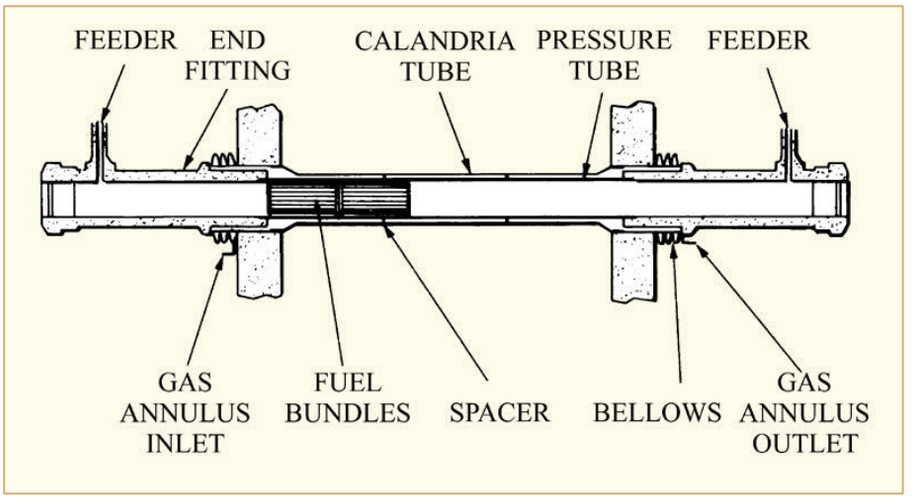


Figure 3-3: Schematic diagram of CANDU fuel channel [Coleman, 2002]

Figure 3-4 is a schematic diagram of a CANDU fuel bundle. The 500 mm long fuel bundle comprises a number of elements, up to 43 in some designs. The fuel elements consist of tubes – sheathing - made from Zircaloy-4 in the cold-worked and stress-relieved condition, containing the fuel pellets and He filler gas sealed with Zircaloy-4 end plugs that are welded to Zircaloy-4 end-plates to maintain the shape of the bundle. Appendages, consisting of bearing pads and spacer pads, are attached by brazing, which produces heat-affected zones containing a range of microstructures from Widmanstätten structure to equiaxed grains.

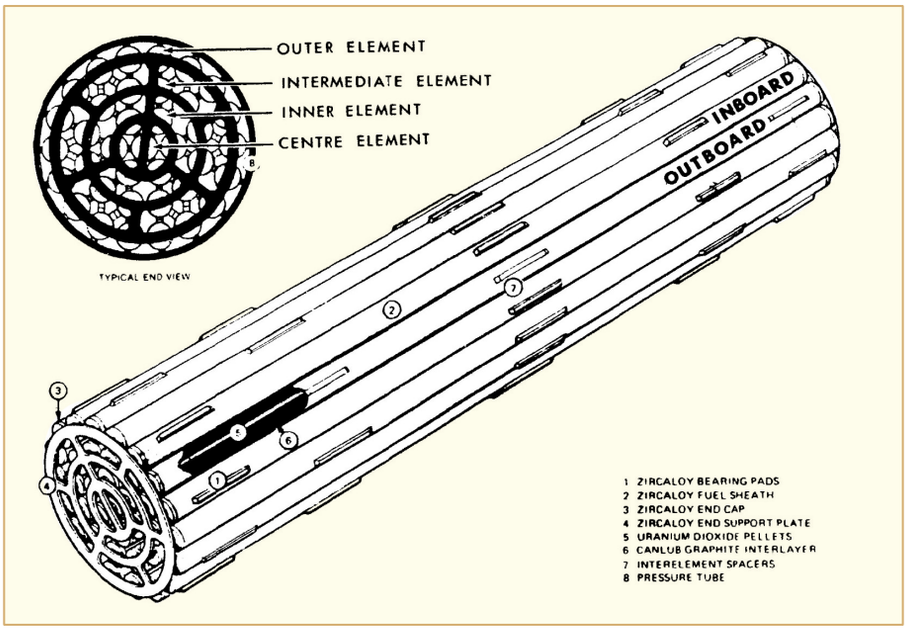


Figure 3-4: Schematic diagram of CANDU fuel bundle [Coleman, 2002]

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Some of the differences between typical fuel cladding and operating conditions in PWR and CANDU are summarised in Table 3-1.

Table 3-1: Typical parameters of fuel in PWRs and CANDUs

	PWR	CANDU
Assembly or bundle configuration	Square	Circular
Number of rods or elements	200	37
Orientation	Vertical	Horizontal
Cladding material	Zircaloy-4, Zirlo, M5	Zircaloy-4
Cladding length (m)	4	0.5
Cladding outside diameter (mm)	9.5	13.1
Cladding wall thickness (mm)	0.6	0.4
Internal gas	He	He
Initial gas pressure (MPa)	2	0.1
Fuel	UO_2	UO_2
U- 235 (%)	≤5	0.7
Peak neutron flux x 10^{17} n/m^2 .s)	8	5
Initial linear power (kW/m)	30	50
Burn-up (GW.d/t U)	50	8
Lifetime (d)	1000	400
Heat-transport fluid	H_20	D_2O
Maximum fluid pressure (MPa)	15.5	11
Maximum cladding temperature (C°)	350	330
Fuel replacement	Reactor shutdown	On power

These differences are reflected in some of the requirements and expectations for post-irradiation examination of fuel:

- The short length of the CANDU fuel bundle allows it to be easily accommodated in moderately sized hot cells and examined as a whole.
- Hydrogen isotopes are picked-up during corrosion of the cladding. In CANDU, concentrations of deuterium as well as protium (light hydrogen) have to be measured.
- Early during service in CANDU the cladding collapses onto the UO_2 fuel pellets whereas in a PWR the cladding has hard contact only after considerable burnup.

To aid removal of a fuel channel from a power reactor, the components are cut into various lengths, ≤ 3 m, at the reactor site. These pieces too are short enough to be easily accommodated in the hot-cells.

Material removed from power reactors is transported from site in a transportation flask. A typical flask is depicted in Figure 3-5 [Celovsky, et al., 2003]. When empty it weighs 5550 kg. Flasks are designed to meet international regulations for the safe transport of radioactive materials (IAEA, 1985, 2012). Use throughout the world should be anticipated with transport by road, rail, air and sea. The loading and unloading must be simple and flexible and the flask should be straightforward to clean and decontaminate. Materials from reactors have various quantities of radioactivity and various dimensions.

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

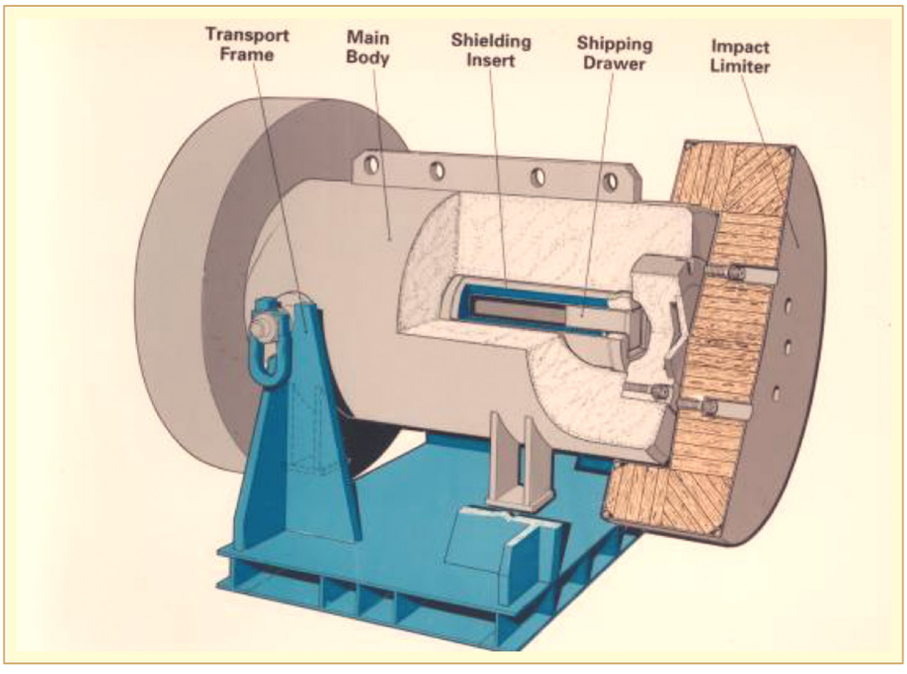


Figure 3-5: Cutaway illustration of material transport flask [Celovsky et al., 2003]

To accommodate these ranges the internal design can be flexible by providing much shielding for fuel from power reactors, up to 54 kCi (2000 TBq), but less for materials other than fuel, < 1 kCi (37 TBq). Figure 3-6 provides a typical internal drawer to accommodate a fuel bundle.

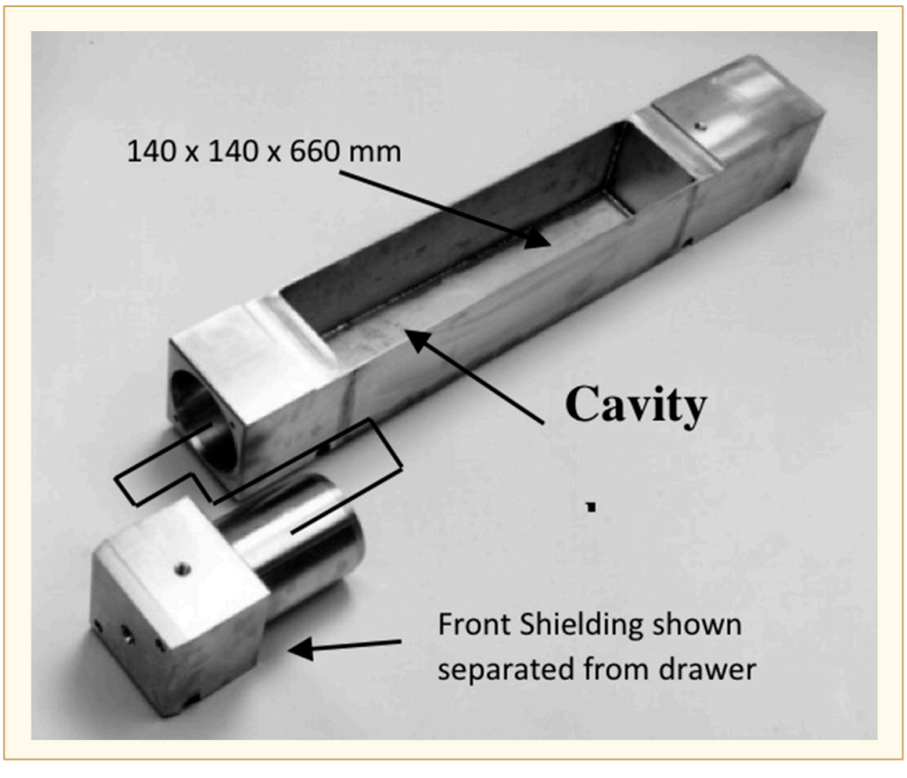


Figure 3-6: Removable drawer for inserting CANDU fuel into transport flask [Celovsky et al., 2003]

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Decay heat from fuel has also to be accommodated. The requirements for shielding material, usually Pb, can be separated from requirements for structural integrity and containment using 304 stainless steel and flexibility is provided by using different designs of inserts for each type of item. To account for clearances, a cavity size of 140 mm by 660 mm is required since in CANDU the largest diameter component is a calandria tube while the length is that of a fuel bundle is 500 mm. To meet the insult from potential accidents, one must show that the integrity of the gamma shielding and the containment system of the flask is maintained. Testing involves a *puncture test* – dropping the flask from a height of 1 m onto a 150 mm diameter pin located on an unyielding surface – *drop tests* - dropping the flask from 9 m onto an unyielding surface at various orientations – a *fire test* included a maximum surface temperature of 800°C maintained for 1800s. Wear-and-tear from usage is accommodated by frequent inspection and maintaining a supply of spare parts, for example, O-ring seals. Personnel are protected by frequent decontaminations of the flask.

Depending on the size of the material being transported, it is placed directly in the hot-cells or received in a large pool of water, called a bay, where first examinations and measurements are performed. Some preliminary specimen selection and cutting may be performed in the bays. Subsequently the material is moved to the hot-cells in a protective flask for detailed examination and testing.

3.3 Handling irradiated materials at Canadian Nuclear Laboratories (CNL), Chalk River, Ontario, Canada

[Trudell, 2016; Cheadle et al, 1988]

Canadian Nuclear Laboratories (CNL) is Canada's main nuclear science and technology laboratory, dedicated to developing peaceful and innovative applications from nuclear technology. CNL has provided post-irradiation examination of irradiated materials, including nuclear fuels and reactor components from LWR and CANDU, for over fifty years. Its shielded facilities provide a comprehensive set of capabilities, from material handling, sample preparation and materials properties, to dimensional, mechanical, chemical, microscopic, metallographic, ceramographic and spectroscopic examination and analysis.

The licensed nuclear facilities at CNL include 15 cells to perform post-irradiation examination of reactor components and fuel materials. The hot cells are situated in two facilities: the Universal Cells (UC), and the Fuels and Materials Cells (FMC). Chalk River also uses the NRU bays (underwater) to receive, store, and perform preliminary examination on fuel and reactor components, while chemical and surface science analyses are performed in the Analytical Chemistry and Materials Sciences Laboratories in support of the PIE campaigns.

3.3.1 The Universal Cells (UC) Facility

This facility is primarily used for non-destructive post-irradiation examinations. The Universal Cells include three cells, two of which are multi-purpose cells that can accommodate a wide variety of testing and analytical equipment, from non-destructive visual and dimensional examination to profilometry, gamma scanning, and fission gas analysis (in conjunction with CNL's on-site analytical chemistry laboratory). The Universal Cells are equipped with a stereomicroscope for viewing and inspecting bundles and elements. The items to be inspected are placed on a remotely operated stage for easy manipulation and rotation allowing for a complete inspection. The 10 megapixel colour cameras are capable of magnifications of 8.4x to 37.7x. The third cell is primarily used for cobalt-60 processing. The Universal Cells can receive, size-reduce, and prepare samples for analysis from materials up to 20 metric tons (22 short tons) in weight and 5.4 meters (17.7 feet) in length. Spent fuel from LWRs, CANDUs and research reactors have been examined in these cells. The cell dimensions are given in Table 3-2.

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Table 3-2: Universal cell dimensions

Cell	Inside Dimensions (m) (wxdxh)	Shielding	Primary Function
Universal Cell 1 (UC1)	2.7 x 2.4 x 4.6	1.1 m concrete	Co-60 isotope processing
Universal Cell 2 (UC2)	2.7 x 2.4 x 4.6	1.1 m concrete	Receiving & mechanical testing
Universal Cell 3 (UC3)	4.9 x 1.8 x 4.0	1.1 m concrete	Receiving & general purpose

3.3.2 The Fuel & Materials Cells (FMC) Facility

The Fuel & Materials Cells are primarily for the destructive examination of irradiated fuels and reactor components. The Fuel & Materials Cells contain microscopic and spectroscopic analytical equipment for scanning electron microscope (SEM), Fourier transform infrared spectroscopy (FTIR), alpha/beta autoradiography, and light examination, as well as precision mechanical testing of material strength to ASTM standards. There are also three specialized cells, mechanical testing cells (MTC), dedicated to basic mechanical testing and examination of non-fissile materials. The cell dimensions are given in Table 3-3.

Table 3-3: Dimensions of Relevant Fuel & Materials Cells (FMC)

Cell	Inside Dimensions (m) (wxdxh)	Shielding	Primary Function
FMC 2	3.7 x 1.8 x 3.9	0.9 m concrete	General Purpose – Temporary Fuel Storage, Gas Puncture + Fission Gas Capture
FMC 3	5.0 x 1.7 x 3.5	0.25 m lead	Fuel Sectioning, Leak Testing, Metallography, Ceramography, Sample Preparation
FMC 4, 5, 6 & 7	1.0 x 1.0 x 1.0	0.13 m lead	Light Microscopy
FMC 10	2.4 x 1.2 x 2.2	0.5 m concrete	Clean - DSC & precision weighing

3.3.3 The NRU spent fuel rod bays

The spent fuel (rod) bays associated with the NRU reactor serve a multi-purpose function in delivering PIE services:

- The bays can accommodate the unloading of large flasks that cannot be unloaded directly into the hot cells.
- Fuel and fuel channel components can be stored in the bays for an interim period while awaiting examination in the hot cells.
- Visual examination of fuel and components can be performed underwater using a portable telescope and camera set-up.

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

References

Armstrong, J., Daniels, T., and Montin, J., *Post-Irradiation Examination of the 37m Fuel Bundle at Chalk River Laboratories (AECL),* 12th International Conference on CANDU Fuel, 2013.

Abolhassani S, Bart G. and Jakob A., *Examination of the chemical composition of irradiated zirconium based fuel claddings at the metal/oxide interface by TEM*, J. Nucl. Materials Vol. 399, pp. 1-12, 2010.

Adamson R. et al., *Corrosion Mechanisms in Zirconium Alloys*, ZIRAT12/IZNA7 Special Topic Report, ANT International, Mölnlycke, Sweden, 2007/2008.

Adamson R. et al., *ZIRAT16/IZNA11 Annual Report*, ANT International, Mölnlycke, Sweden, 2011.

Allen, et al., *Determination and Interpretation of Texture Evolution during Fabrication of a Zirconium Alloy*, J. of ASTM International, Vol. 5, No 1, paper ID JAI101255, 2009 (16th ASTM Zr Symposium).

Bickel, G.A. et al., *The Determinination of Hydrogen and Deuterium in Zr-2.5Nb material by Hot Vacuum Extraction Mass Spectrometry,* J. Nucl. Mater., Vol. 306, pp. 21-29, 2002.

Bouffioux P. and Rupa N., *Impact of Hydrogen on Plasticity and Creep of Unirradiated Zircaloy-4 Cladding Tubes*, Proc. 12th Int. Symp. on Zr in the Nucl. Ind., Toronto, ON., ASTM-STP-1354, p.p. 399-422, 1998.

Carter, T.J. et al., *Effects of End-of-Life Power Ramping on UO_2 Fuel,* Atomic Energy of Canada Limited Report AECL-10417, 1991.

Carter, T.J., *The Effect of UO_2 Pellet Shape on Strains Induced in Collapsible Zircaloy Cladding,* Atomic Energy of Canada Limited Report AECL-5978, 1977.

Cassidy, R.M. et al., *Dynamic Ion Exchange Chromatography for the Determination of Number of Fissions in Uranium Dioxide Fuels,* Analytical Chemistry, Vol. 58, pp.1181-1186, 1986.

Causey, A.R., Urbanic, V.F., and Coleman, C.E., *In-Reactor Oxidation of Crevices and Cracks in Cold-Worked Zr-2.5 wt.% Nb*, J.Nucl. Mater., Vol. 71, pp. 25-35, 1977.

Celovsky, A., Lesco, R., Gale, B., and Sypes, J., *A Review of a Radioactive Material Shipping Container including Design, Testing, Upgrading Compliance Program and Shipping Logistics*, 2003 ASME Pressure Vessels and Piping Conference Cleveland, Ohio, USA, July 20-24, 2003, Atomic Energy of Canada Limited Report AECL-CONF 1370.

Chassie, G.G. et al., *ELESTRES 2.1 Computer Code for High Burnup CANDU Fuel Performance Analysis,* 11th International Conference on CANDU Fuel, October 17-20, 2010.

Cheadle, B.A. et al., *Examination of Core Components Removed from CANDU Reactors,* Atomic Energy of Canada Limited Report AECL-97l0, 1988.

CNL Fuel post-irradiation examination facilities, Sept. 2016

Coleman, C.E., *Simulating the Behavior of Zirconium-Alloy Components in Nuclear Reactors,* ASTM STP-1423, pp. 3-19, 2002.

Cornell, R.M., *An electron microscope examination of matrix fission-gas bubbles in irradiated UO2*, JNM 38, pp. 319-328, 1971.

Cox B. and Rudling P., *Hydriding Mechanisms and Impact on Fuel Performance*, ZIRAT5, Special Topic Report, ANT International, Mölnlycke, Sweden, 2000.

de Carlan Y. et al., *Influence of Iron in the Nucleation of <c> Component Dislocation Loops in Irradiated Zircaloy-4*, Zirconium in the Nuclear Industry: 11th Int'l Symposium, ASTM STP 1295, E. R. Bradley and G. P. Sabol, Eds., American Society for Testing and Materials, 648-653, 1996.

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

DeAbreu, R.F. et al., *Temperature and Neutron Flux Dependence of In-Reactor Creep for Cold-worked Zr-2.5Nb,* 18th ASTM Symposium on Zirconium in the Nuclear Industry, Hilton Head, 2016.

Diez, D., *Metallography – an Introduction, How to Reveal Microstructural Features of Metals and Alloys, Leica Microsystems*, October 18, 2013.

Kristopher Zanotto at GE Vallecitos Nuclear Center, *Email communications*

Feng G. Li. M., and Wang F., *Status and Activities of Post-Irradiation Examinations on Nuclear Fuel in the Nuclear Power Institute of China*, Hot Cell Post-Irradiation Examination and Poolside Inspection of Nuclear Fuel Proceedings of the IAEA–HOTLAB

Field, G.J., Dunn, J.T., and Cheadle, B.A., *Analysis of the Pressure Tube Failure at Pickering NGS A Unit 2,* Can. Met. Quart., Vol. 24, pp.181-188, 1985.

Fielding R., *IAEA TWGFPT- United States Country Report*, Vienna, April 18-20, 2011

Floyd, M.R., Novak, J., and Truant, P.T., *Fission-Gas Release in Fuel Performing to Extended Burnups in Ontario Hydro Nuclear Generating Stations,* Atomic Energy of Canada Limited Report AECL-10636, 1992.

Foltz,J. and Hugo,R., *Recent Advances In EBSD Deformation Analysis, Advanced Materials & Processes*, April, 2016.

Gaillac, A., Lemaignan, C., and Barberis, P., *Damage Build-up in Zr Alloys Mechnaical Processing and Impacts on Quality of Cold Pilgering Product*, 16th Int. Symposium on Zirconium in the Nuclear Industry, Chengde, China, May 2010.

Garzarolli, F., Adamson, R.B. and Colemn, C.E., *ZIRAT20/IZNA15 , Microstructure of Zirconium Alloys and Effects on Performance*, Special Topics Report, ANT International, Mölnlycke, Sweden, 2015.

Garzarolli, F., Adamson,R.B. and Colemn, C.E. , *ZIRAT20/IZNA15 , Microstructure of Zirconium Alloys and Effects on Performance*, Special Topics Report, ANT International, Mölnlycke, Sweden, 2015.

Gavillet, *Didier: email communications*, 2016

Griffiths M., Holt R. A. and Rogerson A., *Microstructural aspects of accelerated deformation of Zircaloy nuclear reactor components during service*, J. Nucl. Mat. 225, pp. 245-258, 1995.

Guler, B., Kalenchuk, D., and Celovsky, A., *Innovation in Pressure Tube Life Assessment,* 6th CNS Conference on CANDU Maintenance, 2003 November 16-18, Atomic Energy of Canada Limited Report AECL-CONF 1374.

Hardy, D.G., *The Effect of Neutron Irradiation on the Mechanical Properties of Zirconium Alloy Fuel Cladding in Uniaxial and Biaxial Tests,* ASTM STP 484, pp. 215-258, 1970.

Hastings, I.J., Smith, A.D., Fehrenbach, P.J., and Carter, T.J., *Fission gas release from power-ramped UO_2 fuel,* J. Nucl. Mater., Vol.139, pp. 106-112, (1986).

Hayashi H. et al., *Outside-in failure of BWR segment rods during power ramp tests, Fuel failure in water reactors: Causes and mitigation*, IAEA-TECDOC-1345, Proceedings of a Technical Meeting held in Bratislava, Slovakia, 17–21 June, 2002.

Hirsch, P. et al., *Electron Microscopy of Thin Crystals*, 1977.

Holt R.A., *In-reactor Deformation of Zirconium Alloy Components*, 15th ASTM International Symposium: Zirconium in the Nuclear Industry, ASTM STP 1505 , pp.3-18, Sunriver, OR, June 2007.(Journal of ASTM International, Vol.5, No.6, 2008).

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Holt, R.A., *In-Reactor Deformation of Zirconium Alloy Components,* J. ASTM International, Vol. 6, Paper ID JAI 101354, 2008.

IAEA Post Irradiation Examination Facilities Database, https://infcis.iaea.org/PIE/PIEMain.asp?Order=1&RPage=1&Page=1&RightP=List, 2012

IAEA RCM-3 in NFD, *PIE Activities in NFD Hot Laboratory*, Sep. 2014.

IAEA Technical report series no. 322, *Guidebook on non-destructive examination of water reactor fuel*, International Atomic Energy Agency, Vienna, 1991.

IAEA Technical report series no. 385, *Guidebook on destructive examination of water reactor fuel*, International Atomic Energy Agency, Vienna, 1997.

IAEA Technical Reports Series No. 305, *Guidebook on Destructive Examination of Water Reactor Fuel*, International Atomic Energy Agency, 1997.

IAEA, *Delayed Hydride Cracking in Zirconium Alloys in Pressure Tube Nuclear Reactors,* IAEA-TECDOC-1410, International Atomic Energy Agency, Vienna, 2004

IAEA, *Regulations for the Safe Transport of Radioactive Materials,* Safety Series No.6, International Atomic Energy Agency, Vienna, 1985.

IAEA, *Regulations for the Safe Transport of Radioactive Materials,* Specific Safety Requirements No. SSR-6, International Atomic Energy Agency, Vienna, 2012.

ICN website, http://www.nuclear.ro/en/departments/lepi.php

IFE Nuclear Materials Technology, Institute for Energy Technology – Kjeller, Norway, 2015

IMEF, *Cells brochure of Irradiated Materials Examination Facility*, KAERI, 2009.

INL, *Post Irradiation Examination Guide, Idaho National Laboratory*, INL/MIS-15-35828, 2015

Jacques P., Lefebvre F. and Lemaignan C., *Deformation-corrosion interactions for Zr alloys during I-SCC crack initiation: Part I: Chemical contributions*, J. Nucl. Mater. 264, pp. 239-248, 1999.

Janzen, P., Joynes, R., Green, L.W., and Urbanic, V. *Monitoring Pressure Tube Health by Micro-Sampling,* Fourth IAEA Technical Committee Meeting on PHWRs, Korea, April 1996, Atomic Energy of Canada Limited Report AECL-CONF-113.

Jädernäs D., Corleoni F., Puranen A., Granfors M., Lysell G., Tejland P., Lutz D. and Hallstadius L., *Microstructural and Chemical Characterization of Ramp Tested Additive Fuel*, Top Fuel 2013, Charlotte, North Carolina, USA, American Nucler Society, 2013.

KAERI Post-Irradiation Examination Facility (PIEF), 2015

Khatamian, D., Ling, V.C., *Hydrogen Solubility Limits in α- and β-zirconium*, J. Alloys Cmpds., Vol. 253-254, pp.162 – 166, 1997.

Kim Y-S, *PWR fuel failure analysis due to hydriding based on pie data, Fuel failure in water reactors: Causes and mitigation*, IAEA-TECDOC-1345, Proceedings of a Technical Meeting held in Bratislava, Slovakia, 17–21 June, 2002.

Kubo T., Kobayashi Y. and Uchikoshi, H., *Determination of fracture strength of delta-zirconium hydrides embedded in zirconium matrix at high temperatures*, J. Nuclear Materials 435, pp. 222-230, 2013.

Langford, R.M. and Clinton, C., *In situ lift-out using a FIB-SEM system*, Micron, 35 (7), pp. 607-611, 2004.

LECA-STAR, *Irradiated Fuel Examination Laboratory and Spent Fuel Reconditionning*, Brochure, CEA Cadarache, 2015

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Nomenclature

AGR	Advanced Gas cooled Reactors
AKL	Active Metals Laboratory
ASTM	American Society for Testing and Materials
ATR	Advanced Test Reactor
BF	Bright Field
BWR	Boiling Water Reactor
CANDU	Canada Deuterium Uranium Reactor
CARR	China Advanced Research Reactor
CEFR	China Experimental Fast Reactor
CERT	Constant Extension Rate Testing
CGR	Crack Growth Rate testing
Ci	Curie
CIAE	China Institute of Atomic Energy
CLAB	*Centralt mellanlager för använt kärnbränsle*
CNL	Canadian Nuclear Laboratories
CT	Compact Tension
DBTT	Ductile to Brittle Transition Temperature
DE	Destructive Examination
DF	Dark Field
DHC	Delayed Hydride Cracking
DIC	Differential Interference Contrast
DOT	Department of Transportation
EBSD	Electron Back Scatter Diffraction
ECP	Element Contact Profilometer
ECR	Equivalent Cladding Removed
ECT	Eddy Current Trace
EDAX	Energy Dispersive X-ray Analysis
EELS	Electron Energy Loss Spectroscopy
EHS	Environmental Health and Safety
EPMA	Electron probe microanalysis
EXAFS	X-ray Absorption Fine Structure
FA	Fuel Assembly
FIB	Focused Ion Beam
FMEF	Fuel and Material Examination Facility
FTIR	Fourier Transform Infrared Spectroscopy
HCL	Hot Cell Laboratory
HFEF	Hot Fuel Examination Facility
HPGe	Hyper Pure Germanium
HPLC	High Performance Liquid Chromatography
HRX	Hardening Relaxation Test
HVE	Hot Vacuum Extraction
IAEA	International Atomic Energy Agency
ICN	Institute for Nuclear Research
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled Optical Emission Spectrometry
ID	Inner Diameter
IFE	Institute for Energy Technology
IMCL	Irradiated Materials Characterization Laboratory
IMEF	Irradiated Materials Examination Facility
IMTL	Irradiated Materials Testing Laboratory
INL	Idaho National Laboratory
IRAS	Infrared Reflection-Absorption Spectroscopy
ISCC	Irradiation assisted Stress Corrosion Cracking
ITU	Institute for Trans-uranium Elements
JMTR	Japan Material Test Reactor
KAERI	Korea Atomic Energy Research Institute
LECI	Laboratory for Studies on Irradiated Fuel

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.

Unit Conversion

TEMPERATURE		
°C + 273.15 = K		°C*1.8 +32 = °F
T(K)	T(°C)	T(°F)
273	**0**	32
289	16	61
298	25	77
373	**100**	212
473	**200**	392
573	**300**	572
633	360	680
673	**400**	752
773	**500**	932
783	510	950
793	520	968
823	550	1022
833	560	1040
873	**600**	1112
878	605	1121
893	620	1148
923	650	1202
973	**700**	1292
1023	750	1382
1053	780	1436
1073	**800**	1472
1136	863	1585
1143	870	1598
1173	**900**	1652
1273	**1000**	1832
1343	1070	1958
1478	1204	**2200**

Radioactivity	
1 Sv	= 100 Rem
1 Ci	= 3.7 x 10^{10} Bq = 37 GBq
1 Bq	= 1 s^{-1}

MASS	
kg	lbs
0.454	**1**
1	2.20

DISTANCE	
x (µm)	x (mils)
0.6	0.02
1	0.04
5	0.20
10	0.39
20	0.79
25	0.98
25.4	**1.00**
100	3.94

PRESSURE		
bar	MPa	psi
1	0.1	14
10	**1**	142
70	7	995
70.4	7.04	**1000**
100	10	1421
130	13	1847
155	15.5	2203
704	70.4	**10000**
1000	100	14211

STRESS INTENSITY FACTOR	
MPa$\sqrt{m}$	ksi$\sqrt{inch}$
0.91	**1**
1	1.10

Copyright © Advanced Nuclear Technology International Europe AB, ANT International, 2016.