Boosting your Excellence through Knowledge and Training

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ZIRAT™

Zirconium Alloy Technology Programme

The ZIRAT19 deliverables.
For information on earlier published ZIRAT Special Topic Reports please see *page 12*.

The Annual ZIRAT Programme is focused on fuel assembly material issues and open to nuclear utilities. In total, 32 organisations were members in 2013, representing more than 111 nuclear units worldwide. This programme was started in 1996.

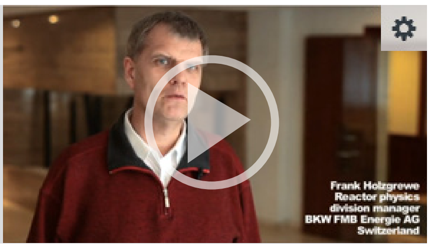
Deliverables

ANT International will provide the ZIRAT Members with the following in January–February time frame:

- Hardbound copy(-ies) in colour of the Special Topic Reports (STRs) and hardbound copy(-ies) of the ZIRAT Annual Report (AR). The ZIRAT Annual Report covers the results presented during the year. The hardbound colour ZIRAT Annual Report and Special Topic Reports will be provided as soon as they are printed with the aim of delivery before the Seminars in February–March.
- Searchable CD-ROM(-s) with the following contents:
  - High-resolution pdf files with the complete ZIRAT Annual Report and the Special Topic Reports in colour.
    - > The files can be copied to a company server, with full read access for everybody with access to the server.
    - > The contents from ZIRAT Annual Report and the Special Topic Reports in pdf-format can be printed.
      Also, the contents from the pdf-files can be copied and pasted electronically into other documents, e.g. Word files.

  The CD-ROM(-s) of the ZIRAT AR and of the STRs will be provided before the Seminars (see below).
- Two similar Seminars will be held to present the results of the ZIRAT Programme in USA and in Europe in February-March. All the ZIRAT presentation material will be provided to the customers prior to the Seminar. This will enable the customers to print out the presentation material, e.g. in colour with high resolution. The number of full time employees per Member that may attend meetings is limited to eight (8) people per organisation. The language of the ZIRAT Programme will be English.
- The authors will be available for consulting throughout the year. A few telephone or e-mail consultations requiring no additional work are provided at no additional cost to Members.

Listen to Frank Holzgreve,
Reactor Physics Division Manager at BKW.

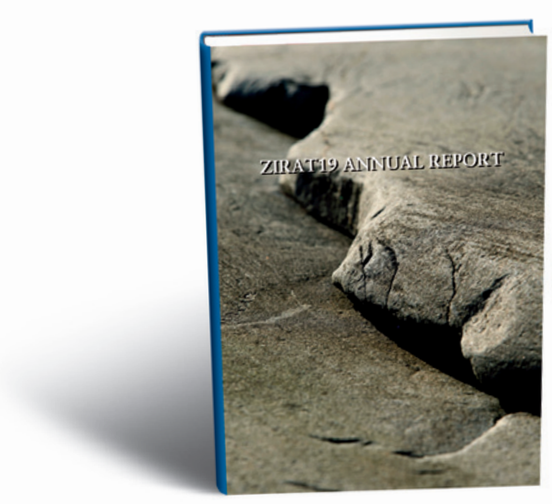


"We find ZIRAT a great help and, in a way, it's like having an extra person in the team"

TED DARBY
Senior Co. Specialist, Rolls-Royce PLC

[Read more]

ZIRAT19 Programme



The overall objective of the ZIRAT Programme is to enable the nuclear utilities and laboratories to:

- Gain increased understanding of material behaviour related to successful core operation and evaluations of options for the back end of the fuel cycle.

The objective is met through review and evaluation of the most recent data on zirconium alloys, identification of the most important new information, and discussion of its significance in relation to fuel performance now and in the future. Included in the review are topics on materials research and development, fabrication, component design and in-reactor performance.

The evaluations are based on the large amount of non-proprietary data presented at technical meetings, published in the literature and provided through discussions with zirconium materials manufacturers.

The open literature information will be collected throughout the year and the data most important to the utilities will be selected for the Annual Report. The large collective experience gained by the reviewers in past and current projects is an important factor in making the evaluation, hence ensuring that the presented compiled information is put in perspective, and that the most important information is emphasized. The data will be useful to utilities to assist them in evaluating:

- New and potential fuel performance problems and performance limits.
- The effect of new data on current fuel design bases.
- Qualifications desirable for new design features.
- The effect of modified or new fabrication processes on properties.
- Potential use of new Quality Control (QC) methods.
- QC requirements for new materials features.
- Qualification needs for new alloys.
- Lessons learned from fuel performance regarding design bases, fabrication process control, QC, and reactor operation.

This information will help utility staff to implement actions to maintain or improve fuel reliability.

Although the value of recent data endures, the specific technical issues affected by the recent data tend to change with time.

The ZIRAT19 Annual Report will start with a short introduction that will give the background and the current understanding of the topic typically based upon previous ZIRAT reviews. The introductory part will be followed by the review of the relevant data presented since the last ZIRAT review, i.e. ZIRAT18. In addition, each topic will have a final summary sub-section that will provide conclusions and an updated view of the understanding given in the introductory part.

The last section in the ZIRAT19 Annual Report will summarise the current issues related to fuel performance and list the data needed to resolve these issues.

The following, currently important, issues are intended to be specifically addressed.

Burnup Achievements and Fuel Performance Issues

- Trends in fuel operating conditions.
- High burnup fuel performance summary.
- Fuel reliability.
- Fuel performance related utility concerns.
- Fuel related regulatory issues of concerns to utilities.

Fabrication

Changes in zirconium alloy fabrication and QC methods and their potential effect on performance.

In-Reactor Performance of Zr Alloys

- Irradiation effects on microstructure of Zr alloy components such as:
  Fuel cladding, liner, guide tube, grid/spacer, fuel channel and pressure tube materials.
- The impact of alloying elements, microstructure, and irradiation conditions (temperature, power history, fast flux, fast dose, PWR, BWR and VVER water chemistry) on:
  - Corrosion and hydrogen pickup mechanisms, redistribution, effects on mechanical and corrosion properties, and dimensional stability.
  - Mechanical properties (e.g. yield and ultimate yield strength, ductility, fracture toughness, fatigue, Delayed Hydride Cracking, Pellet Cladding Interaction)
  - Dimensional stability (irradiation growth, creep, relaxation).
- Recent primary fuel failures (fretting, corrosion, hydriding, Pellet Cladding Interaction (PCI), Pellet Cladding Mechanical Interaction (PCMI)) and secondary degradation, suggested remedies to improve failure resistance, important design and fabrication issues, and impact of plant operation.
- Relationship of fuel rod characteristics to performance in Loss of Coolant Accident (LOCA) and Reactivity Initiated Accident (RIA).
- The direct and indirect impact of water chemistry, CRUD, and chemical additions on the fuel performance.
- Utility and regulator perspectives including burn-up limits based upon the data presented in the ZIRAT19 base Report.

Intermediate storage

Fuel related issues in dry storage.

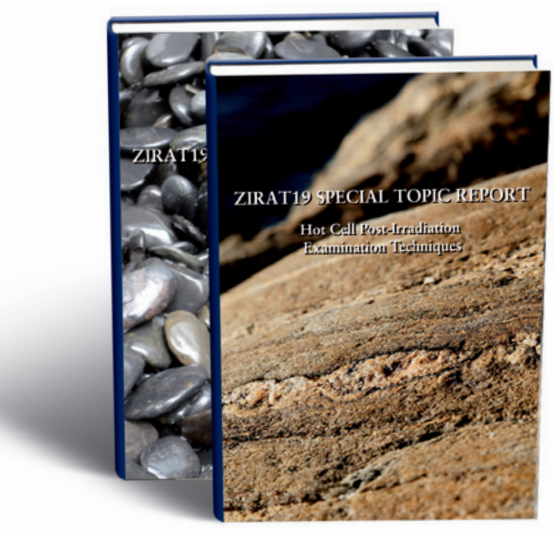
"The ZIRAT Annual Reports provide excellent reference material for our new scientists and engineers and are a valuable resource for scientists like myself who wish to stay current with advances in nuclear materials R&D"

MALCOLM GRIFFITHS

Manager for the Radiation Damage and Deformation Program and the Deformation Technology Branch at AECL Chalk River, Canada

Read more

ZIRAT19 Special Topic Report



In addition to the ZIRAT19 Annual Report, two Special Topic Reports will be prepared on Hot Cell Post-Irradiation Examination Techniques and Ion Bombardment.

The Special Topic Reports will cover the range from basic information to current knowledge and be written and explained in such a way that engineers and researchers not familiar with the topic can easily follow the STRs, find and grasp the appropriate information. This means that the STRs could be used by the organisations in the training of their internal staff with or without the additional assistance of ANT International staff. The background for selecting topics and proposed contents of the Reports are discussed in detail below.

Hot Cell Post-Irradiation Examination Techniques

The growing operational demands on nuclear fuel, such as longer fuel cycles, higher burn-ups, and use of transient regimes, call for more robust fuel designs and more radiation resistant materials. Implementation of new materials and fuel designs that are able to meet these more challenging conditions requires adequate operational feedback and practical verification of models for prediction of fuel behavior. 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.

Post Irradiation Examination (PIE) is the study of used nuclear materials such as fuel rods and rest of the fuel bundle hardware (water rods/guide tubes, spacers/grids, and channel boxes). It has several purposes. It is known that by examination of used fuel the failure modes which occur during normal use (and the manner in which the fuel will behave during an accident) can be studied. In addition information is gained which enables the users of fuel to assure themselves of its quality and it also assists in the development of new fuels. When fuel rod(s) fail in a Light Water Reactor (LWR) in-core and pool-side examinations are performed to locate the failure and determine the cause of failure. If these examinations are inconclusive the failed rods, along with some sound sibling rods, are sent to a hot cell facility for further examinations and tests for root-cause analysis.

The objectives of the hot cell examination of failed and sound sibling rods are to;

1. characterize the fuel rod conditions associated with failure,
2. identify the fuel failure mechanism, and
3. provide insight into the root cause of the failures.

The objectives of the hot cell examination of the fuel bundle hardware vary with the component being examined. The hot cell examinations/testing include a number of tasks selected to address these objectives using available hot cell capabilities.

This Special Topic Report (STR) will provide an overview about the status of post-irradiation examination (PIE) and inspection techniques for nuclear fuel and their applications for analysis of materials degradation during fuel operation in a reactor core. Emphasis will be given to advanced non-destructive and destructive PIE techniques applied to LWR fuel rods and bundle hardware. The objective of this STR is to provide this knowledge. Below is the intended outline:

1. Introduction
    1.1. Equipment needs
    1.2. Manpower requirements

Section 1: Non-destructive examinations

1. Visual examination
2. Dimensional measurements
3. Determination of in-core orientation of the component
4. Full length gamma scanning of a fuel rod
5. Full length profilometry of a fuel rod
6. Full length Eddy current examination of a fuel rod
7. Fission gas analysis through non-destructive Kr-85 assay
8. Fission gas analysis through gas chromatography
9. Sectioning of a fuel rod
10. Neutron radiography
11. Helium bubble leak test of a failed fuel rod
12. Dye penetrant test
13. Helium sniff test

Section 2: Destructive examinations

1. Cladding metallography
2. Cladding corrosion and pellet-clad gap
3. Cladding hydride distribution
4. Cladding hydrogen measurement
5. Zirconium barrier characterization
6. Fuel pellet ceramography
7. Fuel pellet microgamma scans
8. Mechanical properties measurement
    8.1. Uniaxial tensile tests
    8.2. Ring specimen tests
    8.3. Fatigue testing
    8.4. Creep testing
9. SEM examination
10. TEM examination

Section 3: PIE of fuel hardware

1. PIE of water rods/guide tubes

2. PIE of spacers/grids
3. PIE of channel boxes
    3.1. Coupon sectioning
    3.2. Visual examination
    3.3. Sectioning for metallography and hydrogen measurements
    3.4. Metallography for oxide and remaining wall thickness
    3.5. Hydrogen measurement using hot extraction
    3.6. Estimation of channel bow

Summary

Ion Bombardment

The ability of reactor engineers to predict changes in the dimensions of the reactor core components during service is crucial to the safety and efficiency of reactor operation. Successful core design anticipates dimensional changes due to thermal expansion, stress-induced elastic deformation and, to some extent, large stress plastic deformation of core components. Of greater difficulty is predicting dimensional changes due to the effects of the intense irradiation environment, mainly due to high energy neutrons produced by the fission process. Fuel rods, spacers/grids, channels, guide tubes, tie rods, other structural components, etc. – all undergo irradiation-induced dimensional changes due to irradiation growth, irradiation creep, irradiation-altered plastic deformation, and irradiation-influenced corrosion and hydriding of the zirconium alloy components. These topics and process are routinely covered by the ZIRAT Programmes

This Report reviews the effect of ion irradiation (or ion bombardment, used interchangeably in this report) on not only the standard dimensional stability topics but also the full range of properties that can be influenced by ion irradiation.

The primary questions addressed are:

- What properties of zirconium alloys can ion irradiated simulate (emulate or substitute for) neutron irradiation?
- How, or to what extent, can ion bombardment complement neutron irradiation?

Below is the content list

1. Ion Bombardment Introduction
    1.1 Basic damage
    1.2 Ion penetration
    1.3 Temperature shift
2. Initial studies
3. Amorphization
4. Dislocation loops
    4.1 <a> component dislocation loops
    4.2 <c> component dislocation loops

"An interesting seminar with very useful information and a close overview of the state of art of nuclear fuel. I will recommend the seminar to my colleagues."

IGNACIO COLLAZO
Reload Safety Analyst, Iberdrola

5. Irradiation Creep and Growth
6. Hardness
7. Deformation
8. Solutes and Phases
9. Corrosion
   9.1 Zircaloy - proton bombardment
   9.2 Zr2.5Nb - electron irradiation
   9.3 Miscellaneous corrosion
10. Surface embrittlement
11. Facilities
12. Summary and conclusions

Report authors

The authors are: Mr. Peter Rudling, President of ANT International, Mr. Alfred Strasser, President of Aquarius, Dr. Ron Adamson, formerly at GENE, Vallecitos, Mr. Friedrich Garzarolli, formerly at Framatome ANP, Dr. Charles Patterson, formerly at GNF, Dr. Kit Coleman, earlier at AECL, Dr. David Franklin, formerly Bettis Atomic Power Laboratory, and Dr. Sheikh Tahir Mahmood, formerly at GNF.

Mr. Alfred Strasser, a material scientist, has more than 50 years of experience in core technology, in the design, fabrication and irradiation of nuclear fuels for LWRS, FBRs and test reactors, for 18 years at NDA and United Nuclear, for 22 years at S.M. Stoller and currently as President of Aquarius Services Corp. His activities since 1954 have included for clients worldwide:

- Design and design reviews of nuclear fuels
- Fabrication and audits of fabrication of UO_2 and MOX fuels
- Irradiation testing of advanced fuels
- Failure analyses of fuels and other core and plant components
- Materials technology evaluations
- Effects of water chemistry on fuel and core component performance
- Management of R&D programmes
- Specifications and evaluation of commercial bids for fuel and other core components

Dr. Ron Adamson retired from GE Nuclear Energy in 2000, where he was the manager of Materials Technology. Earlier he graduated from the University of Wisconsin with a B.S. in Mechanical Engineering, an M.S. in Nuclear Engineering and a PhD in Metallurgy. Post-doctoral work on irradiation effects was conducted at AERE, Harwell, England. At the GE Vallecitos Nuclear Center he led research, development and testing programmes for reactor core materials, with special emphasis on zirconium alloys. During his 31 years with GE, Dr. Adamson was actively involved with utilities and the technical community worldwide. He holds 17 patents, has published over 80 technical papers involving nuclear materials technology, and has received several important awards, including the Outstanding Technical Contribution Award from GE Industrial Power Systems, the Mishima Award from the American Nuclear Society, and the Kroll Medal from the ASTM/Kroll Institute. Zirconium alloy areas in which Dr. Adamson has particular interest and experience include: in-reactor dimensional stability; in-reactor corrosion performance and mechanisms; microstructure evolution due to reactor irradiation; mechanical properties of irradiated material; high burnup performance; failure mechanisms and remedies; and fabrication technology. Since retirement he has been actively associated with ANT International, EPRI and others as a consultant in zirconium technology.

Mr. Friedrich Garzarolli retired from Framatome ANP in March 2002, where he has held various managerial and research positions, dealing with fuel rod performance analysis, planning and evaluation of irradiation tests, materials characterisation and evaluation of irradiation effects in materials. His degree as Diplom Ingenieur in metallurgy was obtained from the University of Leoben, Austria, in 1963. He has been active in the following fields:

- Development of new fuel assembly materials, especially cladding for BWRs and PWRs
- Modelling of corrosion for zirconium alloys and stainless steels
- Effect of water chemistry on cladding corrosion
- PCI failures of cladding
- In-reactor dimensional stability
- High-burnup performance
- Failure mechanisms and remedies
- Microstructure evolution due to reactor irradiation

Dr. Charles Patterson retired from Global Nuclear Fuel in 2008 as a Consulting Engineer for Fuel Engineering. During 44 years with GE Nuclear Energy/GNF, he was actively engaged in the development of fuel manufacturing processes, fuel materials, thermal-mechanical and fuel performance models and in the improvement of fuel reliability. This activity involved irradiation and hot cell Programmes in Asia, Europe and the United States to identify in-core material behaviour, validate analytic models and improve fuel reliability. Chuck holds patents in the areas of fuel and cladding materials, fuel assembly design and fuel inspection technology. Dr. Patterson has particular interest and experience in the thermal and mechanical behaviour of fuel, cladding and structural materials, the development of analytic models to describe their behaviour and in the improvement of fuel reliability.

Dr. Kit Coleman has, after receiving a PhD in the UK, spent his working career at the Chalk River Laboratories of AECL. Research interests on zirconium alloys included in-reactor creep, development of improved fuel cladding and pressure tube materials. He retired in 1999 as manager of Material and Mechanics Branch but retains an attachment to AECL as a Researcher Emeritus. He has published over 100 papers on zirconium technology and has received the Russ Ogden Award from ASTM and the Kroll Medal from the ASTM/Kroll Institute. He is on the Advisory Editorial Board of the Journal of Nuclear Materials.

"Excellent meeting... as usual."

FRANK HOLZGREWE
Reactor Physics Division Manager, BKW

Dr. Sheikh Tahir Mahmood retired from Global Nuclear Fuel in 2012 as a Senior Engineer/Technologist for Fuels Engineering at the Vallecitos Nuclear Center. Earlier he received Masters degrees in Physics and Nuclear Technology from abroad and doctorate in Nuclear Engineering from North Carolina State University. His Post-doctoral work on mechanical anisotropy of zirconium alloys and radiation effects on reactor structural materials was done at NCSU and ORNL, respectively. At GE Nuclear Energy/GNF, he was actively engaged in fuel performance and materials technology. This activity involved failure root-cause investigations through hot cell PIE of the failed in-core components, and development and evaluation of material property data bases for new materials developed for in-core use. Tahir has particular interest and experience in mechanical metallurgy, mechanical behavior of fuel, cladding and structural materials, and in-reactor behavior of these materials for improved fuel reliability. He has actively participated in various international nuclear industry research programs.

Mr. Peter Rudling is the President of ANT International, managing the ZIRAT/IZNA/LCC Programmes as well as providing seminars and Handbooks on various fuel related topics to the nuclear industry. Peter was a senior consulting scientist at Vattenfall, the largest Swedish power company. Earlier he has also been a Specialist of Fuel Materials at ABB Atom (now Westinghouse) and a Project Manager at EPRI.

Price and Terms of Payment

The fixed nominal price for the ZIRAT Membership appears in the associated Cover Letter.

Terms and Conditions

The term of ZIRAT19 Programme starts from the date of the purchase order and lasts 12 months onwards.

ANT International shall exercise its best efforts to meet the objectives in this assignment and shall apply to the work professional personnel having the required skills, experience and competence. If the assignment is found to be significantly deficient by the customer within 6 months of its completion, ANT International shall modify the work done within this assignment in such a way that it will become satisfactory to the customer. This modification shall be done without incurring any additional costs to the customer. The total amount of such additional costs due to the modification shall be limited to be less or equal to the amount originally paid to ANT International for this assignment.

It is understood that ANT International is not responsible for any damage, incurred to the customer, their employees, or their plants or to a third party due to the use of the information or the recommendations given within this assignment.

The compiled information and the conclusions, as a result of this work, may be used by the purchasing party for its own use for any purpose provided that the source is given. ANT International retains the rights to the compiled information and the conclusions for other uses.

Nuclear Liability

ANT International and its sub-suppliers, including also suppliers of information and services, of every tier and kind, and everyone engaged by any of them, shall have no liability whatsoever (irrespective of negligence or gross negligence) for any damage or loss whatsoever (including also consequential and indirect loss) resulting from a nuclear incident (as such term is defined in the Paris Convention on third party liability in the field of nuclear energy, as amended from time to time). This shall apply for damage or loss suffered by third parties or the owner and for damage and loss to the nuclear installation, on site property and any other property of any kind, and until the nuclear installation has been definitely decommissioned and irrespective of any termination or cancellation of the proposed work.

Insurances of the owner and of others in respect of a nuclear incident shall exclude any right of recourse against the supplier and his sub-suppliers of every tier and kind.

Contact

For more information and/or an offer welcome to contact *Angela Olpretean* at angela.olpretean@antinternational.com

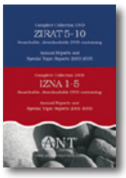
Please also visit our website for the latest updated information, www.antinternational.com

Earlier published ZIRAT Special Topic Reports

Available in hard copy

Available on CD/DVD

Manufacturing of Zr Alloys

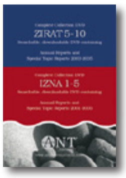


ZIRAT5 STR
Manufacturing of Zirconium Alloy Material

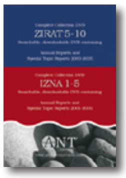
ZIRAT14 STR
Impact of Manufacturing Changes on Zr Alloy In-Pile Performance

ZIRAT11 STR
Manufacturing of Zr-Nb Alloys

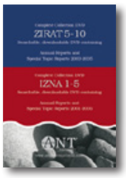
Corrosion and Hydriding of Zr Alloys



ZIRAT6 STR
Water Chemistry and Crud Influence on Cladding Corrosion

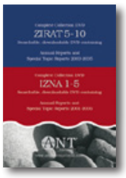


ZIRAT9 STR
Corrosion of Zr-Nb Alloys in PWRs



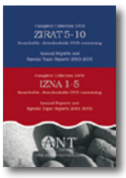
ZIRAT7 STR
Corrosion of Zirconium Alloys

ZIRAT12 STR
Corrosion Mechanisms in Zirconium Alloys

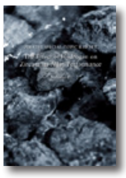


ZIRAT8 STR
The Effects of Zn Injection (PWRs and BWRs) and Noble Metal Chemistry (BWRs) on Fuel Performance

Properties of hydrides and impact on fuel in-reactor performance



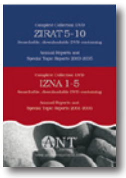
ZIRAT5 STR
Hydriding Mechanisms and Impact on Fuel Performance



ZIRAT13 STR
Effect of Hydrogen on Zirconium Alloy Performance (normal operation, LOCA/RIA and dry storage)

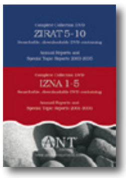
ZIRAT13 STR
Effect of Hydrogen on Zirconium Alloy Properties

Dimensional changes of fuel assemblies/channels and components (fuel assembly/channel bowing, irradiation growth, creep, relaxation, effect of hydrogen)



ZIRAT7 STR
Dimensional Stability of Zirconium Alloys

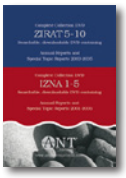
ZIRAT14 STR
In-Reactor Creep of Zirconium Alloys



ZIRAT10 STR
Structural Behaviour of Fuel Components

ZIRAT16 STR
BWR Fuel Channel Distortion

Mechanical properties of Zr Alloys



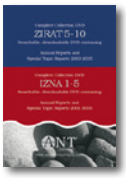
ZIRAT6 STR
Mechanical Properties of Zirconium Alloys

ZIRAT11 STR
Pellet–Cladding Interaction

ZIRAT18 STR
Mechanical Testing of Zirconium Alloys
Volume I

ZIRAT18 STR
Mechanical Testing of Zirconium Alloys
Volume II

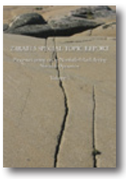
LOCA and RIA fuel performance



ZIRAT9 STR
Loss of Coolant Accidents, LOCA, and Reactivity Initiated Accidents, RIA, in BWRs and PWRs

ZIRAT15 STR
Processes going on in Nonfailed Rod during Accident Conditions (LOCA and RIA)

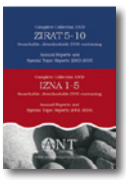
Fuel (UO_2 and MOX) performance



ZIRAT15 STR
Processes going on in Nonfailed Rod during Normal Operation

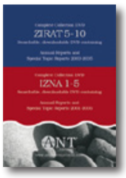
ZIRAT15 STR
Processes going on in Nonfailed Rod during Accident Conditions (LOCA and RIA)

ZIRAT Special Topic Reports on other issues:



ZIRAT8 STR
High Burnup Fuel Issues, their Most Recent Status

ZIRAT12 STR
Welding of Zirconium Alloys



[ZIRAT10 STR](#)
Impact of Irradiation on Material Performance

[ZIRAT16 STR](#)
Performance Evaluation of New Advanced Zr Alloys for PWRs/VVERs

[ZIRAT17 STR](#)
High Strength Nickel Alloys for Fuel Assemblies

[ZIRAT17 STR](#)
High Burnup Fuel Design Issues

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