A.N.T. INTERNATIONAL®

Boosting your Excellence through Knowledge and Training

ZIRAT™

Zirconium Alloy Technology Programme

The ZIRAT18 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 2012, 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 two Special Topic Reports (STR) 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 two 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 two 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.

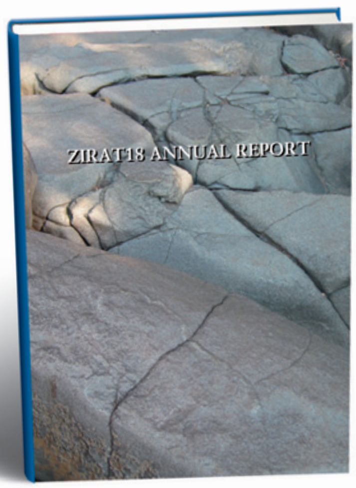
  The CD-ROM(-s) of the ZIRAT AR and of the two STRs will be provided before the Seminars (see below).
- Two similar Seminars will be held to present the results of the ZIRAT Programme in USA and in Europe in February-March. All the ZIRAT presentation material will be provided to the customers prior to 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.

"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

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

ZIRAT18 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 ZIRAT18 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. ZIRAT17. 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 ZIRAT18 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 ZIRAT18 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

ZIRAT18 Special Topic Reports

In addition to the ZIRAT18 Annual Report, two Reports will be prepared on Mechanical Testing Procedures (Volume I and II):

The Special Topic Reports (STRs) 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.

Mechanical testing of zirconium alloys has many uses: to confirm that the material meets the specification, to evaluate new alloys or modifications to old ones, to elucidate mechanisms of strengthening or embrittlement, and to assess the effects of reactor operation. The mechanical response of any material depends on several different parameters such as:

1. specimen geometry,
2. alloy composition and microstructure,
3. loading conditions such as stress state and strain rate, and
4. environment such as temperature, irradiation and ambient chemistry.

Residence in a nuclear reactor presents a severe test for materials. Before evaluating the mechanical properties, knowledge is required on the conditions of normal reactor service with its operational variations, the challenge when spent fuel is stored, and the consequences of accidents. Various mechanical tests are done to simulate the conditions faced by fuel cladding and structural components in the reactor. In applying the results from mechanical testing of zirconium alloys to reactor performance, it is crucial to have a good knowledge of the situation being addressed and how the different critical testing parameters affect the material response so the results are useful to predict performance accurately and satisfy regulatory requirements. The objective of this STR in two volumes is to provide this knowledge. Below is the intended outline of the two volumes.

Mechanical Testing Procedures Volume I

- Introduction
- Basics
  - Basic deformation concepts
    - Stress/Strain
    - Tresca and von Mises approaches
    - Strain energy density
  - Deformation metallurgy
  - Texture of zirconium alloy components
    - Relevance of HCP structure
    - Effects of fabrication processes
    - Techniques of quantifying “texture”, including x-ray diffraction and EBSD procedures
  - Simple fractography

- Tensile Testing
  - Apparatus
  - Effect of specimen geometry and design
  - Details of “ dislocation channeling” and effects on data
- Hardness testing
  - Various techniques
  - Relevance to material behavior
  - Correlations to other tests
- Burst testing
  - Test details and cautions
  - Strain rate effects
  - Relevance
- Creep testing
  - Techniques and cautions
  - Differences between un-irradiated, in-reactor and post-reactor material behavior.
  - Stress relaxation
- Fatigue and fatigue crack propagation testing
  - Basic testing techniques
    - Sample size and design limitations
    - Cautions on data scatter
    - Procedures for data reduction
- Fracture toughness testing
  - Condensed basic theory
  - Restrictions due to reactor component thickness and geometry
  - Review of most relevant techniques
- Delayed hydrogen cracking (DHC)
  - Simple review of phenomena
  - Technique
- Unusual tests
  - SiC component testing techniques
  - “pure” hydride testing techniques

Mechanical Testing Procedures Volume II

- Mechanical design criteria
- Hydrides
  - General phenomenon
  - Effects on testing and data
  - Orientation issues, including hydride re-orientation techniques
  - Relevant effects of hydride concentrations/localization
- Pellet-cladding-interaction/Stress corrosion cracking (PCI/SCC)
  - In-reactor simulation
    - Basic ramp test techniques
    - Requirements for valid evaluations
  - Ex-reactor simulation
    - Necessary elements of the test
      - Chemistry
      - Specimen and system design
      - Loading requirements

- Pellet-cladding-mechanical interaction (PCMI)
  - High strain rate ramps as related to outside–inside cracking
    - Ex-reactor test techniques
    - Relevance to DHC and hydride cracking
  - Reactivity-initiated accidents (RIA)
    - In reactor simulation
      - CABRI and NSSR (Japan) testing
      - Brief review of advantages and deficiencies
    - Ex-reactor simulations
      - Test requirements
        - Stress/strain state
        - Temperature
        - Strain rate
    - Various specimen and test designs
    - Brief review of data reductions and failure criteria
- Loss-of-coolant accident (LOCA)
  - Regimes –ballooning and loss of ductility
  - Test requirements for proper simulation
  - Types of specimens
    - Advantages and deficiencies
- Seismic testing
  - Conditions
  - Testing techniques
- Dry storage
  - Cask drop simulations
  - Hydrogen and hydride issues
  - Hydride re-orientation techniques
  - Creep testing techniques , and relevance
  - Ductility testing issues
    - Specimen design
    - Test conditions
      - Temperature
      - Strain rate
- Creep rupture (as applied to Zr2.5Nb pressure tubes)
  - Specific phenomena
  - Testing and evaluation
- Clad splitting (degradation of failed fuel)
  - Primary and secondary failures
  - Phenomena
  - Testing techniques and evaluation

"ZIRAT has been of great value to me for a number of reasons"

MATT EYRE
Previously at Exelon Corp.

Read more

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. Gunnar Rönnberg, retired from OKG, 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

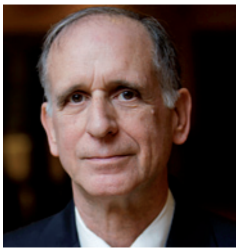
Dr. Charles Patterson retired from Global Nuclear Fuel in 2008 as a Consulting Engineer for Fuel Engineering. During 44 years with GE Nuclear Energy/GNF, he was actively engaged in the development of fuel manufacturing processes, fuel materials, thermal-mechanical and fuel performance models and in the 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.

Dr Gunnar Rönnberg worked from 1973 to 1986 at Studsvik, responsible for reactor physics at the R2 test reactor and managing a large number of fuel test programmes, especially ramp tests for the development of PCIOMRs and of PCI resistent fuel designs. After that he worked 9 years for the Swedish utility Vattenfall, responsible for fuel technology and actively engaged in fuel performance and fuel reliability issues both for PWR and BWR fuel. From 1995 until his retirement in January 2012 he has worked for the utility OKG as a specialist on core and fuel technology. Dr. Rönnberg has a broad interest and experience in core operation issues taking reactor physics as well as thermal hydraulic and mechanical requirements and limitations into account.

"Great conference!"

LEIF MICHELSSON
Fuel Engineer, Nuclear Fuel, TVO



Dr. David Franklin After receiving his PhD in Metallurgy in 1970, Dr. Franklin spent three years at Argonne National Laboratory working on cladding materials for LMFBR fuels. The next 39 years were spent working on light-water-reactor core materials, including three years at Combustion Engineering, 12 years at the Electric Power Research Institute, and 22 years at the Bettis Atomic Power Laboratory. For the last 8 years, he represented the Naval Nuclear Propulsion Program to the Yucca Mountain Project, where he became more familiar with issues associated with storage and disposal of spent nuclear fuel. Dr. Franklin coauthored a book on creep of Zr alloys, published articles on cladding and fuel performance, became a fellow at ASTM International, and was awarded the Kroll medal.

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.

"Excellent meeting... as usual."

FRANK HOLZGREWE
Reactor Physics Division Manager, 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

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 ZIRAT18 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

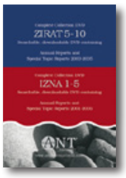
Please also visit our website for the latest updated information, www.antinternational.com

Earlier published ZIRAT Special Topic Reports

Available in hard copy

Available on CD/DVD

Manufacturing of Zr Alloys

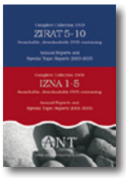


ZIRAT5 STR
Manufacturing of Zirconium Alloy Material

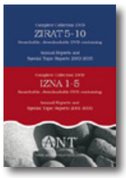
ZIRAT14 STR
Impact of Manufacturing Changes on Zr Alloy In-Pile Performance

ZIRAT11 STR
Manufacturing of Zr-Nb Alloys

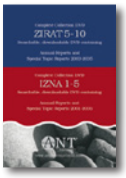
Corrosion and Hydriding of Zr Alloys



ZIRAT6 STR
Water Chemistry and Crud Influence on Cladding Corrosion

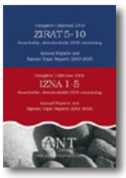


ZIRAT9 STR
Corrosion of Zr-Nb Alloys in PWRs



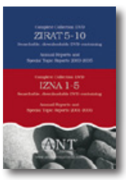
ZIRAT7 STR
Corrosion of Zirconium Alloys

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

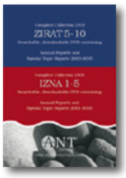


ZIRAT5 STR
Hydriding Mechanisms and Impact on Fuel Performance

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

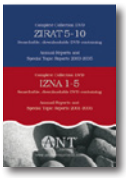
ZIRAT13 STR
Effect of Hydrogen on Zirconium Alloy Properties

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

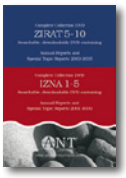
ZIRAT14 STR
In-Reactor Creep of Zirconium Alloys



ZIRAT10 STR
Structural Behaviour of Fuel Components

ZIRAT16 STR
BWR Fuel Channel Distortion

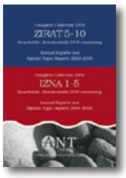
Mechanical properties of Zr Alloys



ZIRAT6 STR
Mechanical Properties of Zirconium Alloys

ZIRAT11 STR
Pellet–Cladding Interaction

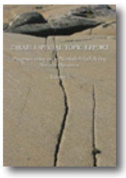
LOCA and RIA fuel performance



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)

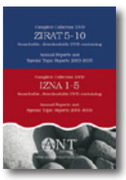
Fuel (UO_2 and MOX) performance



ZIRAT15 STR
Processes going on in Nonfailed Rod during Normal Operation

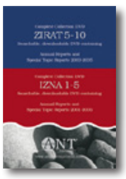
ZIRAT15 STR
Processes going on in Nonfailed Rod during Accident Conditions (LOCA and RIA)

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

Z18

ZIRAT17 STR
High Strength Nickel Alloys
for Fuel Assemblies

ZIRAT17 STR
High Burnup
Fuel Design Issues

A.N.T. INTERNATIONAL®
www.antinternational.com

Office Address: Advanced Nuclear Technology International, Analysvägen 5, SE-435 33 Mölnlycke, Sweden.
Phone: +46 (0)31-88 16 00. Fax: +46 (0)31-88 16 01. info@antinternational.com www.antinternational.com