May 21, 2010

MEMORANDUM TO: Richard Lee, Branch Chief
Fuel and Source Term Branch
Division of Systems Analysis
Office of Nuclear Regulatory Research

FROM: Patrick Raynaud, Reactor Systems Engineer ***/RA/***
Fuel and Source Term Branch
Division of Systems Analysis
Office of Nuclear Regulatory Research

SUBJECT: REPORT ON FOREIGN TRAVEL TO Outside of Scope AND CHINA

This report summarizes foreign travel to France and to China in May 2010.

Outside of Scope

On May 9-13, 2010, Patrick Raynaud attended the 16th International Symposium on Zirconium in the Nuclear Industry, organized by the ASTM International B10 committee on refractory metals. The symposium took place at the Intercontinental Hotel and Conference Center in Chengdu, Sichuan Province, China. During the symposium, Patrick Raynaud gave a presentation on the work he performed while working on his Ph.D. at Penn State University.

The information discussed at these meetings does not require Commission attention. However, some of this information is sensitive and is intended for internal use only.

Enclosure:
Trip Report

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Enclosure:
Trip Report

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NRC INTERNATIONAL TRIP REPORT

Subject

This report summarizes foreign travel to Outside of Scope and to China in May 2010.

Outside of Scope

On May 9-13, 2010, Patrick Raynaud attended the 16th International Symposium on Zirconium in the Nuclear Industry, organized by the ASTM International B10 Committee on Refractory Metals. The symposium took place at the Intercontinental Hotel and Conference Center in Chengdu, Sichuan Province, China. During the symposium, Patrick Raynaud gave a presentation on the work he performed while working on his Ph.D. at Penn State University. This meeting will hereafter be referred to as the Symposium.

This trip report is divided in two parts: the first part covers the trip to Outside of Scope the second covers the trip to China

The information discussed at these meetings does not require Commission attention. However, some of this information is sensitive and is intended for internal use only.

Dates of Travel, Countries and Organizations Visited

Outside of Scope

May 7-14, 2010
Travel to Chengdu, China
Organizations visited / Meetings Attended:
ASTM International: 16th International Symposium on Zirconium in the Nuclear Industry

Author, Title, and Agency Affiliation

Patrick A.C. Raynaud, Reactor Systems Engineer
Fuels and Source Term Branch
Division of Systems Analysis
Office of Nuclear Regulatory Research

Enclosure

Outside of Scope

Outside of Scope

Outside of Scope

Outside of Scope

Outside of Scope

Outside of Scope

Outside of Scope

Outside of Scope

Part 2: 16th International Symposium on Zirconium in the Nuclear Industry in Chengdu, Sichuan Province, China

Background or Purpose

The ASTM International B10 Committee on Reactive and Refractory Metals and Alloys sponsors the International Symposium on Zirconium in the Nuclear Industry every 3 years. This highly focused and technical symposium is arguably the most prestigious meeting worldwide on the topic of zirconium for nuclear applications. This iteration was the 16th symposium and was held in Chengdu, Sichuan Province, China, between May 9 and May 13, 2010.

There were about 200 attendees from just about every country in the world that has a nuclear industry. The majority of the sessions presented some fundamental research on zirconium and its properties that are relevant for nuclear applications. Two sessions focused on in-pile behavior, failure mechanisms, and transients.

The traveler Patrick Raynaud was attending the symposium in order to obtain state-of-the-art information on zirconium research. During the symposium, he presented some of his Ph.D. research, which was performed at Penn State University under an NRC grant prior his employment with NRC.

Summary of Pertinent Points and Issues

The symposium only had one session at a time, so that all the presentations could be seen by all the attendees. There were seven sessions for presentations, each lasting a half day, totaling 42 platform presentations. One afternoon was reserved for a poster session. The program of the conference is available under ML101410129 [1]. All the presentations and posters should be available on the conference website in the next few weeks, however, Patrick Raynaud was able to obtain some of the presentations ahead of time, directly from the presenters. In addition, all the papers presented at the conference will be published online in the Journal of ASTM International, and an ASTM Special Technical Publication (STP) of the proceedings will be published within one or two years.

The symposium opened with remarks by the Governor of the City of Chengdu, who declared that China was honored to have been chosen to host the symposium, and expressed his hopes for the development of a clean nuclear power industry in China, as well as the development of the nuclear materials industry necessary to support the power industry.

The President of the Nuclear Power Institute of China (NPIC) took the stage next to announce that the symposium was a great way to expand the knowledge in the field of zirconium. He reminded the audience that China was currently building more nuclear reactors than any other country in the world. He then described the NPIC as a very large R&D organization that has played an important role in the development of Gen II nuclear power plants (NPPs) in China, and is currently supporting the Gen III plants and the development of Gen IV technology.

NPIC declared that it was open to sharing its achievements with other R&D organizations, and encourages exchanges for future zirconium research: "The Chinese government would like to work with you hand in hand to develop international research cooperation on zirconium."

On the first morning, the symposium editorial chair (Pierre Barberis) reminded the attendees of the high quality of the symposium by announcing that about 130 abstracts had been received and reviewed by 50 reviewers, and that only 42 platform presentations and 30 posters were chosen. About a quarter of the papers originated from Asia (Japan, China, India and Korea), a quarter from North America (US and Canada), a quarter from France, and a quarter from the rest of Europe (UK, Sweden, Switzerland, Germany and Norway). There was also one paper from Argentina and one from Russia.

The sessions of the symposium were titled, in chronological order: Basic Metallurgy, Fabrication and Mechanical Properties, Hydrogen Effect, Corrosion – Oxide Layer Characterization, In-pile Behavior, Creep and Deformation, and Failure Mechanisms and Transients. It is obvious from these titles that the organizers' desire was to move from more fundamental scientific research to more applied research as the symposium moved forward in time. The first two sessions were related zirconium properties, the next four were related to degradation mechanisms or in-service behavior, and the last was related to failures as a result of all of the above.

The traveler (Patrick Raynaud) had submitted an abstract which was initially not selected for the symposium. However, due to last minute cancelations and the rejection of a paper which had initially been accepted, the traveler had an opportunity to present research previously performed at Penn State University during his Ph.D. studies. The title of the presentation was "Crack Growth in the Through-Thickness Direction of Hydrided Thin-Wall Zircaloy Sheet", the co-authors were Drs. Arthur Motta and Donald Koss of Penn State, and Dr. Kwai Chan of Southwest Research Institute. The presentation was very well received by the audience, and sparked a number of technical discussions with members of the audience. The presentation slides are available in ADAMS under ML101410123 [2].

Discussion

The papers presented were generally of very high quality. The next paragraphs list some of the more interesting presentations and topics at the symposium, in chronological order.

A Ph.D. study sponsored by Westinghouse on second phase precipitation in Zr-Nb, Zr-Nb-Fe and Zr-Nb-Sn alloys was presented by Dr. Maria Ivermark, see reference [3] (ML101410100). This presentation was interesting because it revealed that Westinghouse's is performing research on Zr-Nb binary alloys (one of which had the same nominal composition as M5 and E110).

On the topic of zirconium alloys texture, two very interesting talks were given on the texture evolution as a function of temperature during the α-β-α phase transformation, in Zr-2.5Nb and Zircaloy-2. These studies used neutron diffraction and synchrotron radiation, respectively, to perform in-situ measurements, see reference [4] (ML101410117) and reference [5] (ML101410125).

Dr Kit Coleman of AECL presented a paper on delayed hydride cracking (DHC) in Zircaloy-4. He showed that DHC can occur in Zircaloy-4, but that no striations were observed, which is very different from that observed in Zr-2.5Nb. The slides from this presentation could not be obtained prior to writing this report.
Dr. Une gave a talk on the hydrogen pickup as a function of corrosion behavior for 3 alloys: Zircalo-2, GNF-Ziron, and VB. The slides from this presentation could not be obtained prior to writing this report.

Kim Colas of Penn State Presented a very interesting in-situ synchrotron radiation experiment allowing the observation of hydride dissolution and precipitation, as well as hydride reorientation under load. The experiment was set up so as to measure diffraction data simultaneously with load and temperature for a pre-hydrided tensile specimen. This is yet another example of the recent trend in performing in-situ experiments with very powerful experimental techniques, which should allow for a much better understanding of phenomena that could only be observed post-facto up until recently. Such techniques could be useful in studying hydride reorientation as a part of the NMSS program on spent fuel. The presentation is available in ADANS under ML101410081 [6].

During the corrosion session, Michael Preuss of the University of Manchester presented a very interesting paper on the mechanisms of oxidation in Zircaloy-4, ZIRLO, and Optimized-ZIRLO. Philippe Bossis of CEA presented the corrosion behavior of M5 under different conditions. Finally, Anand Garde of Westinghouse presented a paper titled "Advanced Zirconium alloy for PWR applications", which presented the behavior of the new AXIOM-X5A alloy. Two heat treatment conditions were studied: high temperature process (HTP) and low temperature process (LTP). The hydrogen pickup of HTP-X5A was about 35% lower than that of ZIRLO, with a corrosion behavior that was equal to (for the HTP version) or better (for the LTP version) than ZIRLO. In terms of growth, the HTP showed higher growth than ZIRLO while the LTP may have lower growth.

Another very interesting presentation of new in-situ techniques was given by Mirco Grosse of the Karlsruhe Institute of Technology (KIT). In this presentation, neutron radiography was used during the QUENCH tests to measure hydrogen content and to observe hydrogen distribution and diffusion in real time, see reference [7] (ML1001410095).

A very interesting talk by Valerie Chabretou of AREVA presented an evolution of the M5 alloy, with very small additions of tin and iron,, thus making the composition closer to that of ZIRLO or E635. The slides are available under ML101410071 [8]. A number of in-pile and out-of-pile characterization results were presented. Overall, tin increased the creep resistance, but was detrimental to corrosion. The additions of iron somewhat compensated the detrimental effects of tin on hydriding.

John Foster of Westinghouse gave a talk on the creep behavior of ZIRLO, and presented some in-pile data that may be of interest to NRC, see reference [9] (ML101410092).

Margaret McGrath of the Halden Reactor Project presented the effects of pre-irradiation on irradiation creep and growth of recrystallized Zircaloy-4 guide tubes. This study used a very nice and complex experimental setup to measure growth strains in-pile, see reference [10] (ML101410111).

During the very last session of the symposium, three very interesting presentations were given for which the slides could not be obtained prior to writing this report. Jean Desquines of IRSN presented the DIFFOX code for oxygen diffusion predictions in zirconium alloys, for application to LOCA high temperature diffusion. M. Nakatsuka of Nippon Nuclear Fuel Development Co. presented some high strain rate mechanical and fracture properties of cladding as a function of hydrogen, for application to RIA. Slava Grigoriev of Studsvik presented expansion due to compression (EDC) test data at rapid heating and loading rates, and compared his results to the NSRR tests performed in Japan.

"On the Margins"

Margaret McGrath of the Halden Reactor Project (HRP) informed Patrick Raynaud of HRP's intention to look closely at what out-of-pile tests are being performed in order to decide what to next at Halden in terms of the experimental program. In particular, she mentioned NRC LOCA testing at Studsvik.

Each presentation was followed by 10 minutes for questions and answers. The vast majority of the questions were asked by a relatively small group of people: Arthur Motta (PSU), Joe Rashid (ANATECH), Jean-Christophe Brachet (CEA), Ken Yueh (EPRI), Young-Suk Kim (KAERI), Philippe Bossis (CEA), Marc Daymond (Queen's University), Malcolm Griffiths (AECL), Pierre Barberis (AREVA/CEZUS), Kit Coleman (AECL), Suresh Yagnik (EPRI), Ron Adamson (ex-GE), Slava Grigoriev (Studvik), Johannes Bertsch (PSI), and Jayanta Chakravartty (Bhabha Atomic Research Center).

The Kroll Zirconium Medal Award was given to Brian Cheadle of AECL during the Kroll Award Luncheon on 05/12/2010. Many previous Kroll Award recipients were present at the conference: Frederich Garzarolli, Ronald Adamson, Kit Coleman, Malcolm Griffiths, John Banker, David Franklin, and Viatcheslav Shishov.

The John Schemel Award for best paper at the previous symposium (held in Sunriver, OR in 2007) was given to Z. Zhao, M. Blat-Yrieix, A. Ambard, L. Legras, A. Legris, J.P. Morniroli, and Y. Khin for their paper titled "Characterization of zirconium hydrides and phase field approach to a mesoscopic-scale modeling of their precipitation".

Pending Actions or Planned Next Steps for NRC

None

Points for Commission Consideration or Items of Interest

None

References

[1]. 16th International Symposium on Zirconium in the Nuclear Industry: Program (ML101410129)

[2]. Presentation slides: "Crack Growth in the Through-Thickness Direction of Hydrided Thin-Wall Zircaloy Sheet", P. Raynaud, A. Motta, D. Koss and K. Chan, ASTM 16th Symp. on Zr in the Nuc. Ind., Chengdu, China, 2010 (ML101410123)

[3]. Presentation slides: "Measurement and Modeling of Second Phase Precipitation Kinetics in Zirconium Niobium Alloys", M. Ivermark, J. Robson, M. Preuss, ASTM 16th Symp. on Zr in the Nuc. Ind., Chengdu, China, 2010 (ML101410100)

[4]. Presentation slides: "In Situ Studies of Variant Selection During the α-β-α Phase Transformation in Zr-2.5Nb", P. Mosbruker, M.R. Daymond, R.A. Holt, ASTM 16th Symp. on Zr in the Nuc. Ind., Chengdu, China, 2010 (ML101410117)

[5]. Presentation slides: "Texture evolution of Zircaloy-2 during beta quenching", J. Romero, M. Preuss, R.J. ComstockJ. Quinta da Fonseca, M. Dahlback, L. Hallstadius, ASTM 16th Symp. on Zr in the Nuc. Ind., Chengdu, China, 2010 (ML101410125)

[6]. Presentation slides: "In-situ study of hydride reorientation kinetics using synchrotron radiation", K. Colas, A. Motta, J. Almer, M. Daymond, M. Kerr, ASTM 16th Symp. on Zr in the Nuc. Ind., Chengdu, China, 2010 (ML101410081)

[7]. Presentation slides: "Neutron Radiography: A Powerful Tool for Fast, Quantitative and Non-Destructive Determination of the Hydrogen Concentration and Distribution in Zirconium Alloys", M. Grosse, M. Steinbrück, J. Stuckert, ASTM 16th Symp. on Zr in the Nuc. Ind., Chengdu, China, 2010 (ML101410095)

[8]. Presentation slides: "Ultra low tin quaternary alloys PWR performance - Impact of tin content on corrosion and mechanical resistance", V. Chabretou, P.B. Hoffmann, S. Trapp-Pritsching, G. Garner, P. Barberis, V. Rebeyrolle, J.J. Vermoyal, ASTM 16th Symp. on Zr in the Nuc. Ind., Chengdu, China, 2010 (ML101410071)

[9]. Presentation slides: "ZIRLO Irradiation Creep Stress Dependence in Compression and Tension", J. Foster, R. Baranwal, ASTM 16th Symp. on Zr in the Nuc. Ind., Chengdu, China, 2010 (ML101410092)

[10]. Presentation slides: "Effects of Pre-Irradiation on Irradiation Growth & Creep of Re-Crystallized Zircaloy-4", M. McGrath, S. Yagnik, H. Jenssen, ASTM 16th Symp. on Zr in the Nuc. Ind., Chengdu, China, 2010 (ML101410111)

16th International Symposium on Zirconium in the Nuclear Industry

Sponsored by ASTM Committee B10 on and Refractory Metals and Alloys

May 9-13, 2010
InterContinental Century City Chengdu
Chengdu, Sichuan Province, China

Symposium Chair:	M. Limbäck Westinghouse Electric Sweden Vätserås, Sweden
Symposium Editorial Chair:	P. Barbéris Areva/Cezus Research Centre Ugine, France

SUNDAY, MAY 9, 2010: REGISTRATION

MONDAY, MAY 10, 2010

8:30AM
Opening Remarks
Chengdu Mayor 10 min
NPIC President 10 min
M. Morel, Chairman, ASTM Committee B10 on Reactive and Refractory Metals and Alloys;
M. Limbäck, Symposium Chairman; P. Barbéris, Symposium Editorial Chairman

Presentation of the John Schemel Award for the Best Paper from the 15th International Symposium

SESSION 1: BASIC METALLURGY

Session Chairs: B. Herb and J. Chakravartty

9:00AM
Dynamic Recrystallization in Zirconium Alloys
J.K. Chakravartty, R. Kapoor, A. Sarkar

9:30AM
Measurement and Modelling of Second Phase Precipitation Kinetics in Binary Zirconium Alloys
J. Robson, M. Ivermark, M. Preuss

10:00AM
Effects of Tin and Niobium on Generalized-Stacking-Fault Energy Surface of Zirconium
Y. Udagawa, M. Yamaguchi, T. Tsuru, H. Abe, N. Sekimura, T. Fuketa

10:30AM BREAK

11:00AM
Texture Evolution of Zircaloy-2 during Beta Quenching
J. Romero, J. Quinta da Fonseca, M. Preuss, M. Dahlbäck, R. Comstock, L. Hallstadius

11:30AM
In Situ Study of Variant Selection During the α-β-α Phase Transformation in Zr-2.5Nb
P. Mosbrucker, M.R. Daymond, R.A. Holt

12:00AM
Development of Zr 2.5Nb Pressure Tubes for Advanced CANDU Reactor
G. Bickel, M. Griffiths

12:30PM
Session Summary
Session Chairs

12:45 PM LUNCH

SESSION 2: FABICATION and MECHANICAL PROPERTIES

Session Chairs: M. Preuss and Y. Gaihuan

2:00PM
Impact of the Irradiation Damage Recovery During Transportation on the Subsequent Room Temperature Tensile Behavior of Irradiated Zirconium Alloys
B. Bourdillau, F. Onimus, C. Cappelaere, V. Pivetaud, P. Bouffioux, V. Chabretou, A. Miquet

2.30PM
Segregation in Vacuum Arc Remelted zirconium alloy ingots
A. Jardy, F. Leclerc, M. Revil-Baudard, V. Rebeyrolle

3.00PM
Damage Build-Up in Zirconium Alloys Mechanical Processing and Impacts on Quality of the Cold Pilgering Product
A. Gaillac, C. Lemaignan, P. Barberis

3:30PM BREAK

4:00PM
Effect of Texture on the Anisotropic Thermal Creep of Pressurized Zr-2.5Nb Tubes
W. Li, R.A. Holt

4:30PM
Creep of a Zr-2.5Nb Tube with Orientation and Temperature
Y.S. Kim, S.S. Kim

5:00PM
Polycrystalline Approach of Visco-Plastic Behavior of Zircaloy-4 Recrystallized at 400°C
M. Priser, M. Rautenberg, J.M. Cloué, Ph. Pilvin, X. Feaugas, D. Poquillon

5:30PM
Session Summary
Session Chairs

TUESDAY, MAY 11, 2010

SESSION 3: HYDRIDING – HYDROGEN EFFECT

Session Chairs: P. Rudling and K. Coleman

8:30AM
Crack Growth in the Through-Thickness Direction of Hydrided Thin-Wall Zircaloy Sheet
P. Raynaud, D.A. Koss, A.T. Motta, K.S. Chan

9:00AM
High Temperature Aqueous Corrosion and Deuterium Uptake of Coupons Prepared from the Front and Back Ends of Zr-2.5Nb Pressure Tubes
H.M. Nordin, A.J. Elliot, S.G. Bergin

9:30AM
Hydrogen Absorption Mechanism of Zirconium Alloys Based on the Characterization of Oxide Layer
K. Une, M. Aomi, K. Sakamoto, J. Matsunaga, Y. Etoh, K. Ito, I. Takagi, S. Miyamura, T. Kobayashi, H. Moriyama

10:00AM
In-situ SEM Observation and FEM Analysis of Delayed Hydride Cracking Propagation in Zircaloy-2 Fuel Cladding Tubes
T. Kubo, H. Muta, S. Yamanaka2, M. Uno, K. Ogata

10:30AM BREAK

11:00AM
The Effect of Second Phase Particles on the Hydrogen Uptake Performance of Zirconium Alloys Corroded in Super-Heated Steam
M.Y. Yao, J.H Wang, B.X. Zhou, Q. Li, J.L. Zhang

11:30AM
In-Situ Study of Hydride Reorientation Kinetics Using Synchrotron Radiation
K. Colas, A. Motta, M. Daymond, M. Kerr, J. Almer

12:00AM
Statistical Analysis of Hydride Reorientation Properties in Irradiated Zircaloy-2
S. Valance, J. Bertsch, A.M. Alan

12:30PM
Session Summary
Session Chairs

12:45PM LUNCH

SESSION 4: CORROSION – OXIDE LAYER CHARACTERISATION

Session Chairs: R. Comstock and T. Rui

2:00PM
Detailed Microstructure of the Oxide-Metal Interface Region in Zircaloy-2 After Autoclave Testing
P. Tejland, K. Fagerlund, H-O. Andren, S. Ciuera, T. Andersson, M. Dahlbäck, L. Hallstadius

2:30PM
Study of the Initial Stage and Anisotropic Growth of Oxide Layers Formed on Zircaloy-4
B. X. Zhou, J. C. Peng, M. Y. Yao, Q. Li, S. Xia, C. X. Du, G. Xu

3:00PM
Towards a Mechanistic Understanding of Corrosion Mechanisms in Zirconium Alloys
M. Preuss, S. Lozano-Perez, P. Frankell, D. Hudson, E. Polatidis, N. Ni, J. Weil, C. English, S. Storer, M. Fitzpatrick, F. Wang, Chris Grosvenor, George Smith, John Sykes, Alfred Cerezo, Bob Cottis and Stuart Lyon

3:30PM BREAK

4:00PM
Understanding Crack Formation at the Metal/Oxide Interface during Corrosion of Zirconium Alloys Using a Simple Mechanical Model
A. Ly, A. Ambard, M. Blat-Yrieix, L. Legras, P. Frankel, M. Preuss, C. Curfs, G. Parry, Y. Bréchet

4:30PM
Corrosion of M5 in PWRs: Quantification of Li, B, H and Nb in the Oxide Layers Formed under Different Conditions
Ph. Bossis, C. Raepsaet, M. Tupin, C. Bisor-Melloul, H. Khodja, M. Blat, A. Ambard, A. Miquet, D. Kaczorowski

5:00PM
Advanced Zirconium Alloy for PWR Applications: Update on Alloy A
A. Garde, G. Wikmark, R. Baranwal, R. Kesterson, L. Hallstadius, T. Cook F. Carrera, R. J. Comstock

5:30PM
Session Summary
Session Chairs

WEDNESDAY, MAY 12, 2010

SESSION 5: IN PILE BEHAVIOUR

Session Chairs: B. Cheng and L. Hallstadius

9:00AM
Photoelectrochemical Investigation of Radiation Enhanced Shadow Corrosion Phenomenon
Y.J. Kim, R. Rebak, Y-P. Lin, D. Lutz, D. Crawford, A. Kucuk, B. Cheng

9:30AM
Optimization of Zry-2 for High Burnups
F. Garzarolli, B. Cox, and P. Rudling

10:00AM
Effects of Secondary Phase Particle Dissolution on the In-Reactor Performance of BWR Cladding
S. Valizadeh, G. Ledergerber, S. Abolhassani, R. J. Comstock, D. Jädernäs, M. Dahlback, Erik Mader, G. Zhou, J. Wright, L. Hallstadius

10:30AM BREAK

11:00AM
Neutron irradiated Zircaloy-4: Microstructural Changes Due Reactor Operating Conditions
P. Vizcaíno, P. B. Bozzano, A. V. Flores, A. D. Banchik, R. A. Versaci, R. O. Ríos

11:30AM
Ultra Low Tin Quaternary Alloys In-Pile Performance Impact of Tin Content on Corrosion and Mechanical Resistance
V. Chabretou, P.B. Hoffmann, S. Trapp-Pritsching, G. Garner, P. Barberis, V. Rebeyrolle, J.J. Vermoyal

12:00
Radiation Damage of E635 Alloy under High Dose Irradiation in the VVER-1000 and BOR-60 Reactors
G.P. Kobylyansky, A.E. Novoselov, A.V. Obukhov, Z.E. Ostrovsky, V.N. Shishov, M.M. Peregud, V.A. Markelov

12:30PM
Session Summary
Session Chairs

12:45PM KROLL AWARD LUNCHEON

3:00PM POSTER SESSION
See the poster list at the end of the program.

THURSDAY, MAY 13, 2010

SESSION 6: CREEP and DEFORMATION

Session Chairs: M. McGrath and A. Motta

8:30AM
Simulation of Outside-in Cracking in BWR Fuel Cladding Tubes under Power Ramp
K. Sakamoto, M. Nakatsuka, T. Higuchi

9:00AM
ZIRLO™ Irradiation Creep Stress Dependence in Compression and Tension
J. Foster, R. Baranwal

9:30AM
Neutron Radiography: a Powerful Tool for Fast, Quantitative and Non-Destructive Determination of the Hydrogen Concentration and Distribution in Zirconium Alloys
M. Grosse, M. Steinbrück, J. Stuckert

10:00AM BREAK

10:30AM
Effects of Pre-Irradiation on Irradiation Creep and Growth of Recrystallised Zircaloy-4
M. McGrath, H.K. Jenssen, S. Yagnik

11:00AM
REFLET Experiment in OSIRIS : Relaxation Under Flux for Creep Behaviour of Assembly Components
S. Carassou, C. Duguay, P. Yvon, F. Rozenblum, J.M. Cloué, V. Chabretou, C. Bernaudat, B. Levasseur, A. Maurice, P. Bouffioux, K. Audic

11:30 AM
Further Insight into Zircaloy-2 Channel Bow Mechanism
S. T. Mahmood, P. E. Cantonwine, Y-P. Lin, D. C. Crawford, E. V. Mader, K. Edsinger

12:00PM
Session Summary
Session Chairs

12:15PM LUNCH

SESSION 7: FAILURE MECHANISMS and TRANSIENTS

Session Chairs : J.-C. Brachet and S. Grigoriev

1:30PM
Influence of Steam Pressure or Pre-transient Zirconia Layer on High Temperature Oxidation Kinetics of Zirconium-based Alloys and their Post Transient Mechanical Properties
V. Vandenberghe, P. Crébier, M. Le Saux, J.C. Brachet, D. Hamon, D. Gilbon, B. Hafidi, J.P. Mardon

2:00PM
High Temperature Oxidation and Residual Ductility of Fuel Claddings from Zr-1Nb Alloy Having Different Zirconium Bases
V. Markelov, V.V. Novikov, A.G. Mal'gin, A.Y. Gusev, M.G. Shtutsa, A.G. Ziganshin, S.Y. Kropachev, E.N. Aktuganova, V.E. Donnikov, V.I. Latunin, Y.V. Pimenov

2:30PM
Effect of Hydrogen on Mechanical Properties and Failure Morphology of LWR Fuel Cladding Tubes under Rapid Deformation
M. Nakatsuka, S. Yagnik

3:00PM BREAK

3:30PM
The Iodine-induced Stress Corrosion Crack behavior of Zr-Sn-Nb Alloy at Constant Strain Rate
X. Dai, W. Zhao

4:00PM
RIA Failure of High Burn-up Fuel Rod Irradiated in KKL: Out-of-Pile Mechanical Simulation and Comparison with Pulse Reactor Tests
V. Grigoriev, R. Jakobsson, D. Schrire, G. Ledergerber, T. Sugiyama, F. Nagase, T. Fuketa, L. Hallstadius, S. Valizadeh

4:30PM
Session Summary
Session Chairs

4:40PM
Closing remarks
M. Morel, Chairman, ASTM Committee B10 on Reactive and Refractory Metals and Alloys; M. Limbäck, Symposium Chairman; P. Barberis, Symposium Editorial Chairman

4:50PM The 16th International Symposium adjourns

POSTER SESSION

Critical Temperatures for Delayed Hydride Cracking in N18 Zirconium Alloy
C. Sun, J. Tan, S. Ying, Q. Peng and S. Zhao

Phase Transformations in Zr-Nb-Fe-Sn System Alloys
V.N. Shishov

Secondary Hydriding Criteria under Irradiation Conditions
I.A. Evdokimov, V.V. Likhanskii, A.A. Sorokin, V.D. Kanukova

High-temperature Oxidation Kinetics of 110 Alloy Irradiated Claddings
A. Goryachev, J.J. Kosvintsev, A.J. Leshchenko

Investigation of the Interaction between Gliding Dislocations and Irradiation Induced Loops in Zirconium Alloys
F. Onimus, L. Dupuy, B. Doisneau-Cottignies

Nano-chemical Observations of Zirconium Alloy Corrosion using 3D Atom Probe
D Hudson, Na Ni, D W Saxey, G D W Smith, C R M Grovenor

Effect of Elements on Corrosion behavior of Zr Alloy in 500/10.3MPa Steam
J. Wang, J. Xiong, Z. Miao, S. Ying

Fracture Toughness of a Cold-Worked Zr-2.5Nb Alloy with Temperature and Hydrogen Concentration
Y.S. Kim, D.W. Kim, S.S. Kim

The High Temperature Oxidation Behaviors of N18 Zirconium Alloy
J. Qiu, X. Liu, W. Zhao

How to Obtain in Laboratory Representative Hydride Blisters on Zirconium Alloy: A Survey of Surface Effect
M. Blat-Yrieix, A. Ambard, C. Watroba, A. Miquet, A. Legris

SANS Analyses on Irradiated M5 and Zircaloy-4 Alloys after Annealing
J.L. Béchade, MH. Mathon, D. Gilbon, JP. Mardon, A. Miquet, L. Legras

The Relationship of Matrix Microstructure, Oxide Film Characteristics and Corrosion Resistance of New Zirconium Alloys
H. Zhang, Z. Li, L. Zhou, D. Fruchart , E. K. Hlil, L. Ortega

An Experimental Study of Hydrides in Zirconium Alloys in View of Delayed Hydride Cracking
A. Steuwer, M. Preuss, J. Romero, A-M. Alvarez, J.E. Daniels

Influence of Hydrogen Content on Impact and Fracture Toughness of Zr-alloy Pressure Tubes used in Indian PHWRs
R.N. Singh, U.K. Viswanathan, J.S. Dubey, J.K. Chakravartty

Optimization of the Zirconium Bars Manufacturing using Numerical Simulation
K. Niang, A. Gaillac, JL Aubin

Evaluation of Fracture Toughness and Critical Crack Length of Indian Pressure Tubes
K. S. Balakrishnan, P.K. Shah, J.S. Dubey, S. Anantharaman, S. Chatterjee

Modelling Irradiation Damage Evolution in CANDU Reactor Core Components
G.A. Bickel, S.R. Douglas, M. Griffiths, N. Wang, O.T. Woo, A.W. Buyers

The Effect of ß-quenching and subsequent Ageing Treatments on the Corrosion Resistance of Zircaloy-4
M. Y. Yao, X. Zhang, S. L. Li, J. Q. Geng, J. H. Wang, B. X. Zhou, W. J. Zhao

Recrystallization Behavior of Cold-Rolled Zr-Sn-Nb-Fe Alloy Sheets
J. Chen, B. Luan, Q. Liu, X. Zhang, T. Huang

Effect of Hydrogen Contents on the Mechanical Properties of Zr-Sn-Nb Alloy
J. Zhou, Z. Li, J. Zhang, B. Luan, L. Zhou

Fuel and Cladding Degradations Observed in PHWR Fuel Pins having Weld Defects
P. Mishra, U.K. Viswanathan, V.P. Jathar, J.L.Singh, D.N. Sah, S. Anantharaman

Cladding Deformation Studies on Irradiated Fuel Pins from Indian PHWR
D.N. Sah, U.K. Viswanathan, S. Banerjee, P. Mishra, S. Kumar, S. Anantharaman

Low Cycle Fatigue and Uniaxial Tensile Behavior of Thin-Walled Tubes of Zr-1Nb and Zircaloy-4 at Elevated Temperatures
X. Huang, L. Cai

Microstructural Studies of Heat Treated Zr-2.5 Nb Alloy for Pressure Tube Applications
N. Saibaba, S. K. Jha, S. Tonpe, V. Kumar, Deshmukh, K.V. ManiKrishna, S. Neogy, D. Srivastava, G. K. Dey, R. V. Kulkarni, B.B. Rath, E. Ramadasan and K. Ananthraman

Validation of Weight Function Process-Zone Model for Flaw Evaluation against Delayed Hydride Cracking Initiation
S.X. Xu, D. Kawa, D.A. Scarth

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Crack Growth in the Through-Thickness Direction of Hydrided Thin-Wall Zircaloy Sheet

P. A. Raynaud [1], D. A. Koss [2], A. T. Motta [2], K. S. Chan [3]

[1] U.S. NRC, Washington, DC 20555

[2] Penn State University, University Park, PA 16802

[3] Southwest Research Institute, San Antonio, TX 78228

16th Int. Symp. on Zr in the Nuc. Ind. - Chengdu, China, May 2010

Acknowledgments

- Harold Scott and Ralph Meyer, NRC
- Sébastien Carassou, Olivier Rabouille and Christophe Poussard, CEA Saclay
- Jean Desquines, IRSN Cadarache

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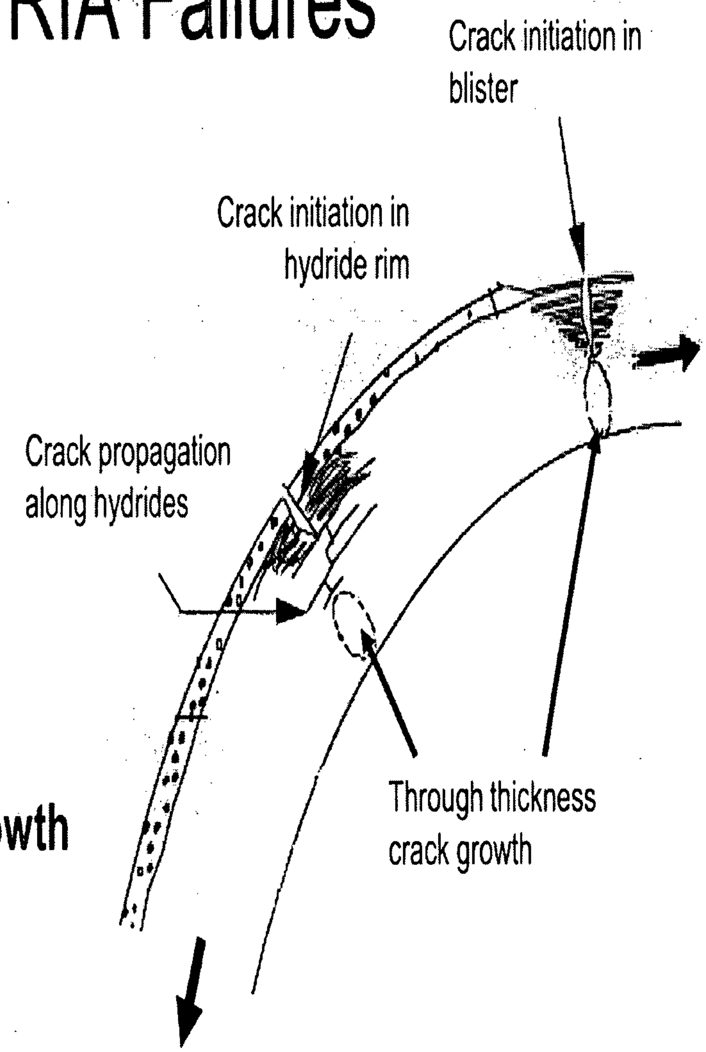
Outline

- Background and motivation
- Experimental and analytical procedures
  - Materials and hydriding
  - Hydride microstructure characterization
  - Fracture toughness testing
- Experimental results
  - Load-displacement behavior
  - Fracture behavior
- Fracture toughness interpretation
  - Fracture mechanics interpretation
  - J-R curve behavior
  - Influence of hydrogen and temperature
- Conclusions

Background – RIA Failures

- Crack initiation and growth due to PCMI
  - Reactivity Insertion Accident
- Crack initiation in reduced ductility zones
  - Hydride rims and blisters
- Failure by **through-thickness crack growth**



➢ To predict failure on the basis of crack growth, it is necessary to know the **fracture toughness** of the material in the **through-thickness** direction

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Motivation

- Many fracture toughness studies on zirconium alloys

  BUT...

- Studies often performed on thick (5mm-6mm) plate or tube configurations
  - Actual cladding tubes have a very thin wall (~600μm)
- Axial crack growth
  - Very few through-thickness crack growth studies
- Little data at 300°C and above
  - In-service temperatures are ~300°C-350°C

➤ ***No studies of <u>through-thickness</u> crack growth in <u>thin-wall</u> components***

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Goals

- The primary purpose of this study is to investigate the fracture toughness behavior for ***through-thickness*** crack growth using ***thin sheet*** specimens of cold work and stress relieved Zircaloy-4 as a model material
  - As a function of hydride microstructure
  - As a function of temperature (up to 375°C)

- Identification the micro-mechanisms that control crack growth resistance as a function of hydride microstructure and temperature

- Achieved by performing a fracture toughness test on 4-point bend specimen containing a linear hydride blister to initiate a crack

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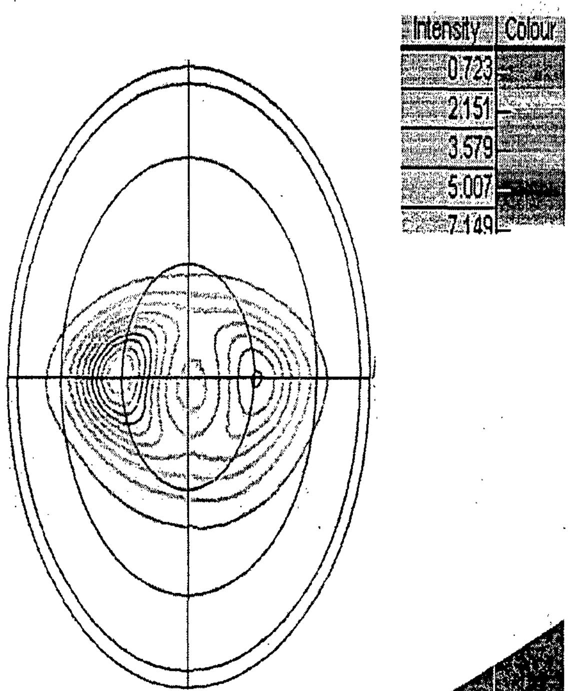
Materials – Texture

- CWSR Zircaloy-4 thin sheet provided by ATI - Wah-Chang
  - Texture and mechanical properties similar to previously studied materials
- Basal poles oriented at ~30° from the sheet normal in the transverse direction

Direction		Normal Radial	Transverse Circumferential	Rolling Axial
Present study CWSR sheet	Direct pole figure method	0.59	0.29	0.12
	Inverse pole figure method	0.59	0.31	0.16
Previous studies	CWSR sheet[1]	0.59	0.31	0.05
	CWSR tube[2]	0.58	0.32	0.10

[1]O..N. Pierron, 2003 and [2]P. Delobelle, 1996.



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Materials – Flow Behavior

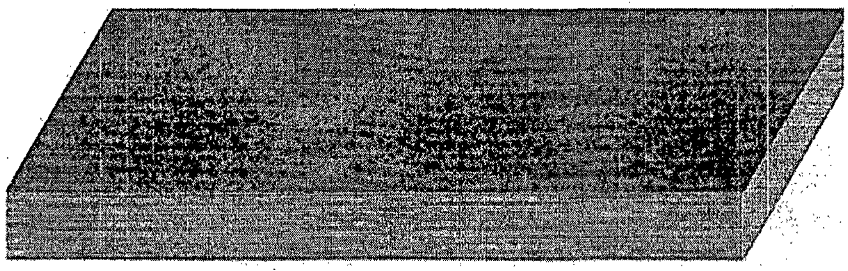
- Material properties in the **transverse direction** after stress relief heat treatment for **2 hours at 520°C**

		$\sigma_{0.2\%}$ (MPa)	n	e_f (%)	P
25°C	Previous studies at PSU with CWSR sheet[1]	573	0.01	19	2.2
	CWSR Sheet (this study)	***575***	***0.018***	***17***	***2.6***
	Unirradiated CWSR Cladding [2]	590	0.068	NA	1.3
300°C	Previous studies at PSU with CWSR sheet[1]	318	0.03	16	1.6
	CWSR Sheet (this study)	***315***	***0.032***	***20***	***1.9***
	Unirradiated CWSR Cladding [2]	350	0.059	NA	1.5
375°C	***CWSR Sheet (this study)***	***290***	***0.027***	***22***	***1.6***

[1] O.N. Pierron, 2003 and [2] T. M. Link, 1998

Hydrogen Charging Procedure

- Oxide removal



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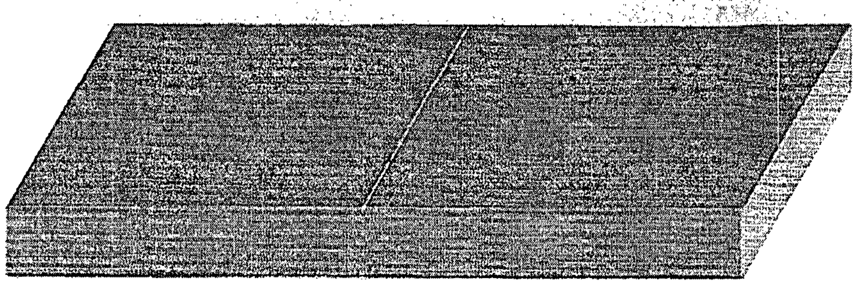
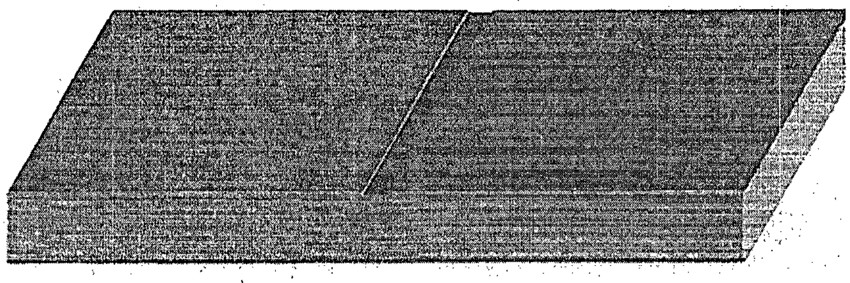
Hydrogen Charging Procedure

- Oxide removal
- Gold sputtering



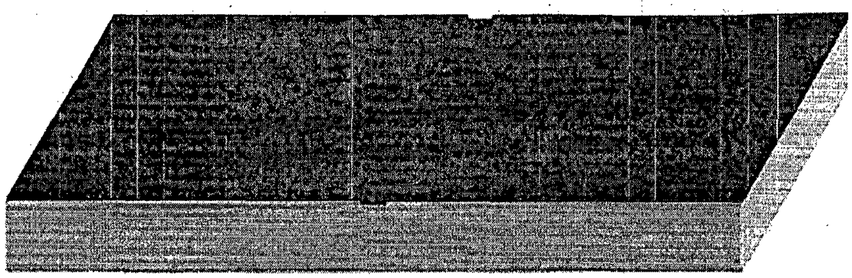
Hydrogen Charging Procedure

- Oxide removal
- Gold sputtering
- Gold removal by scribing



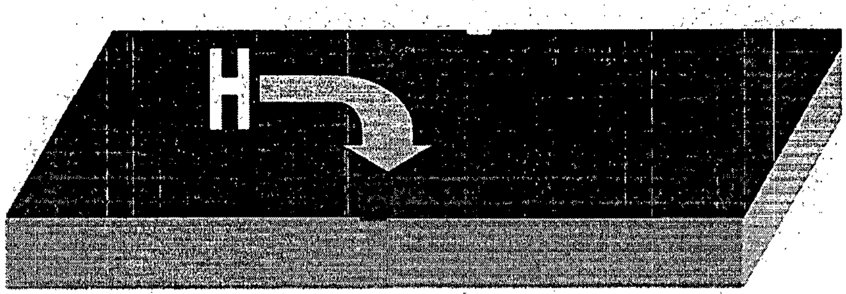
Hydrogen Charging Procedure

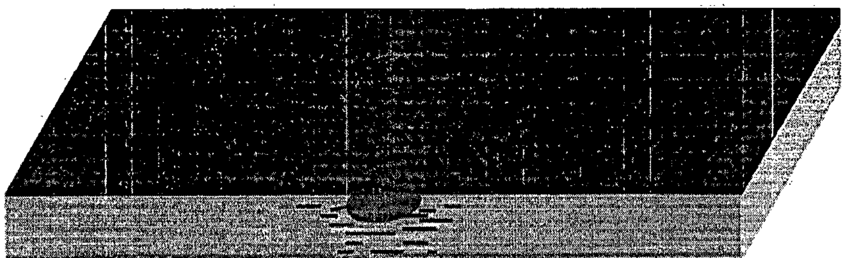
- Oxide removal
- Gold sputtering
- Gold removal by scribing
- Nickel deposition/window

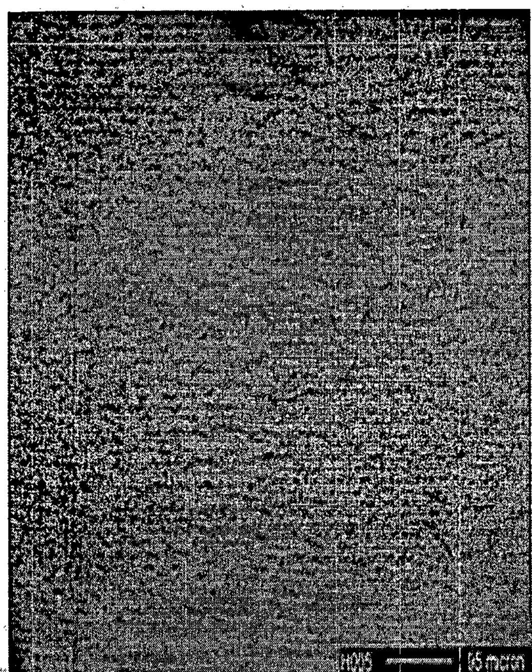


Hydrogen Charging Procedure

- Oxide removal
- Gold sputtering
- Gold removal by scribing
- Nickel deposition/window
- Gas-charging in H_2/Ar at 400°C and 9psi pressure

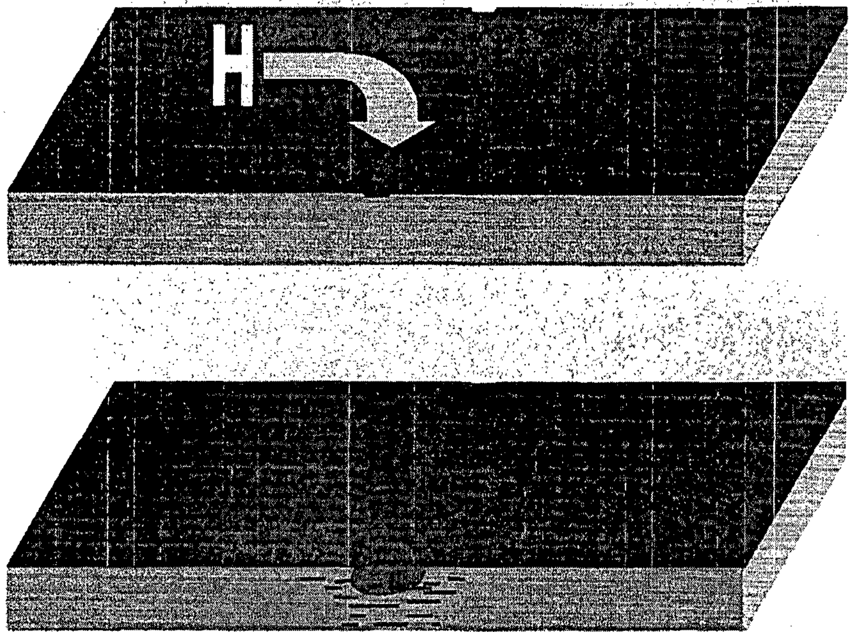


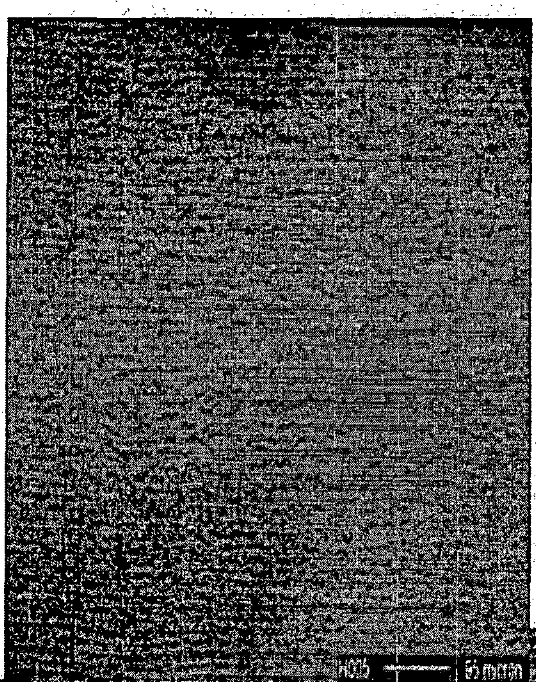




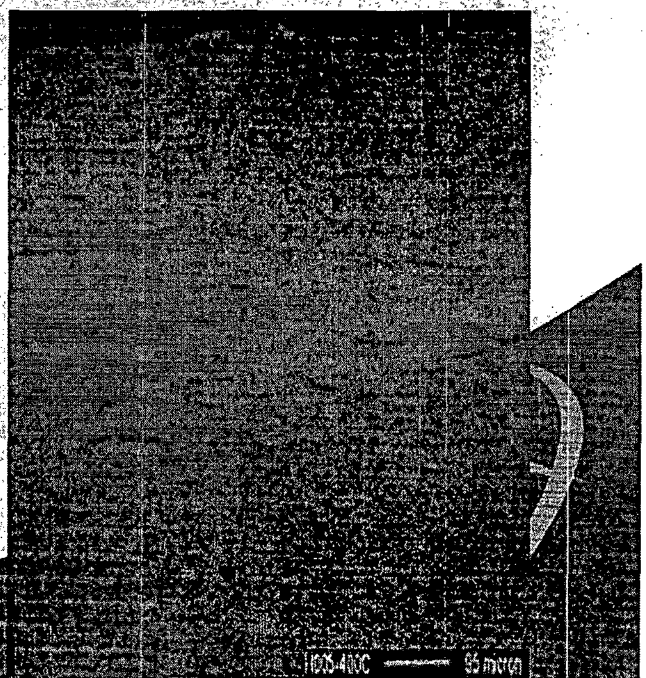
Hydrogen Charging Procedure

- Oxide removal
- Gold sputtering
- Gold removal by scribing
- Nickel deposition/window
- Gas-charging in H_2/Ar at 400°C and 9psi pressure
- Annealing



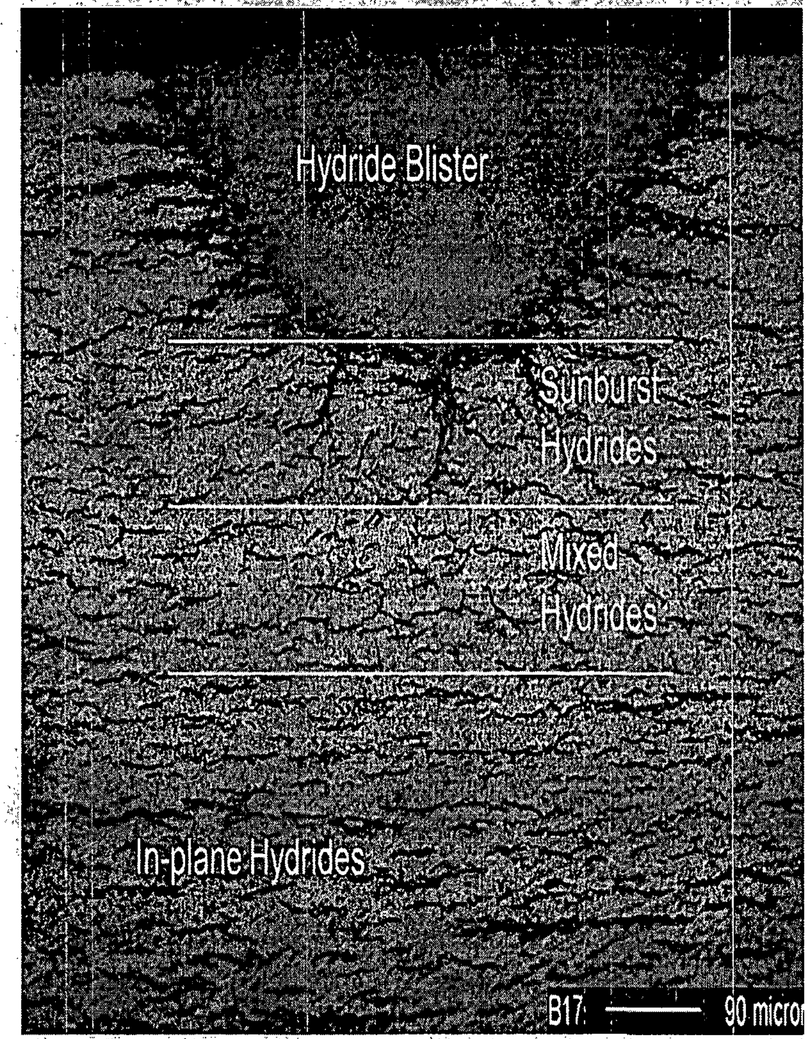


Anneal at 400°C & slow cool



Characterization of Hydride Microstructure

- Hydride microstructure varied through the thickness of the specimens
- Important to characterize the local hydride microstructure to understand its influence on fracture toughness
- Image analysis software was used to obtain a quantitative description of hydride microstructure
  - Image-J was used to predict the hydrogen content
  - Hydromorph was used to calculate the radial hydride content



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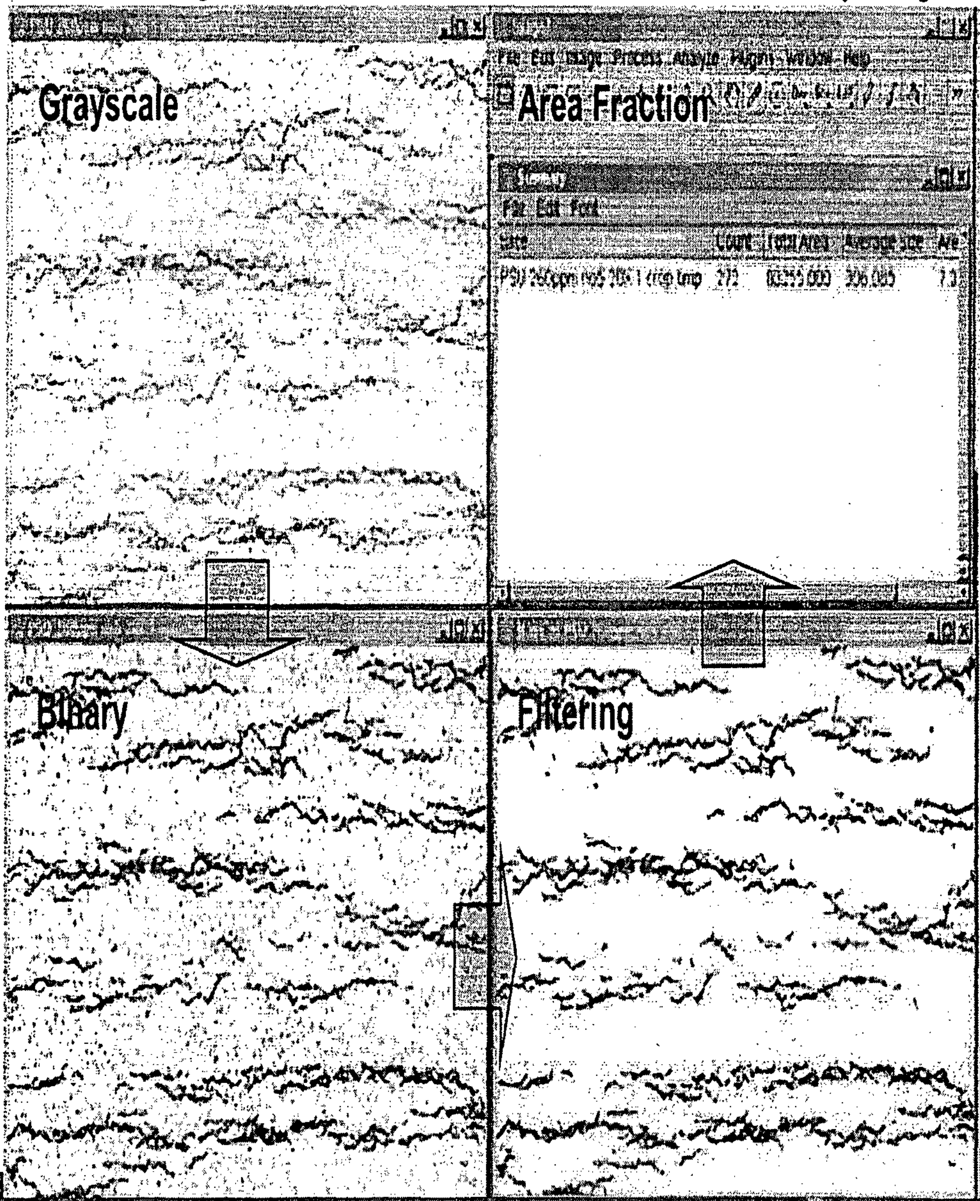
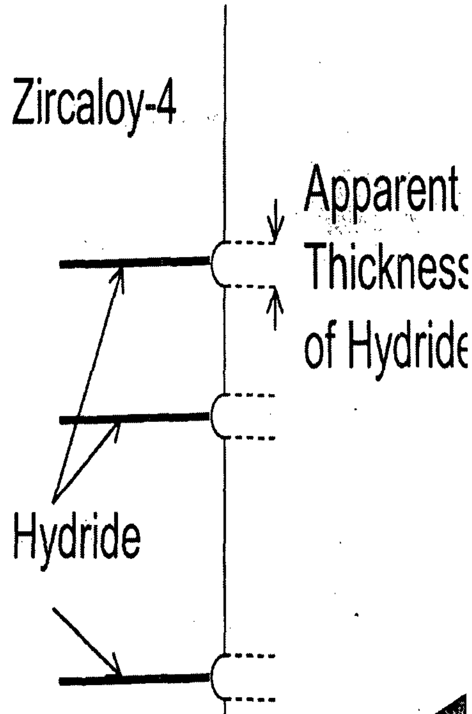
Hydrogen Content Estimation

- Area fraction measurements may be converted to hydrogen contents
- Calculated hydrogen contents were calibrated by hot vacuum extraction
- Etching results in an over-estimation of the hydrogen content by a factor of ~15





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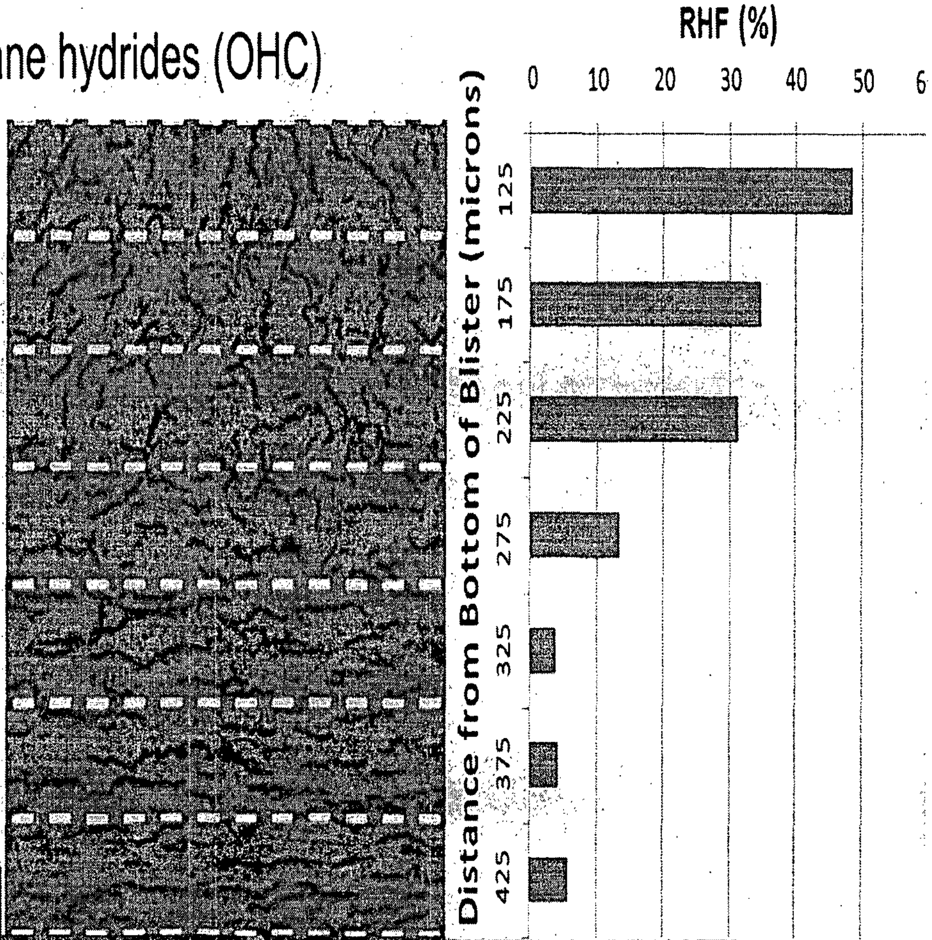
Hydride Orientation
Hydromorph

- Image analysis software developed by the CEA and IRSN
  - Skeletization and indexing of hydrides
  - For each hydride particle, Hydromorph provides length and orientation
- We define:
  - 0°<θ<40° for in-plane hydrides (IHC)
  - 40°<θ<65° for mixed hydrides (MHC)
  - 65°<θ<90° for out-of-plane hydrides (OHC)

$$MHC = \frac{\sum_j L_j^{mixed}}{L_{total}}$$

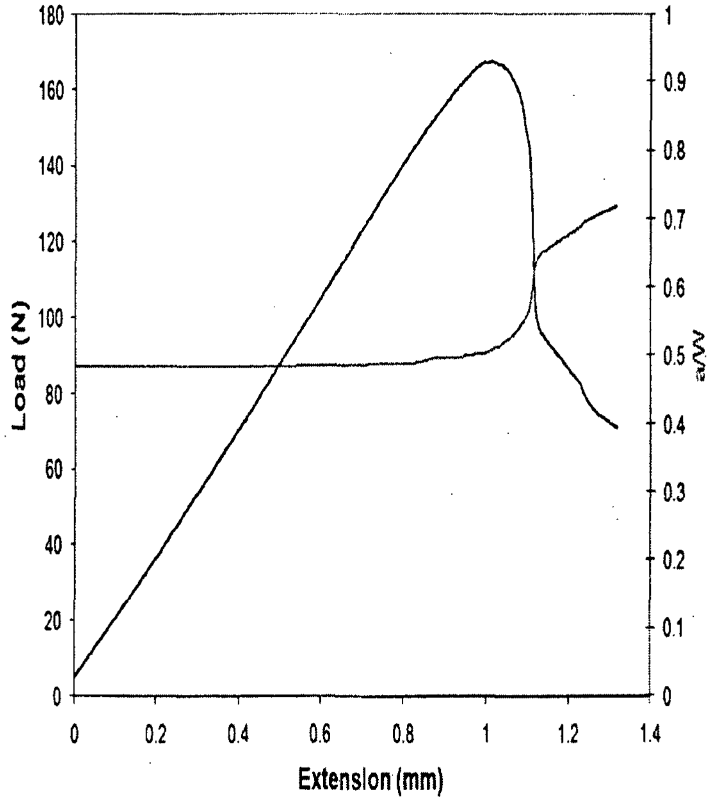
- Radial Hydride Fraction

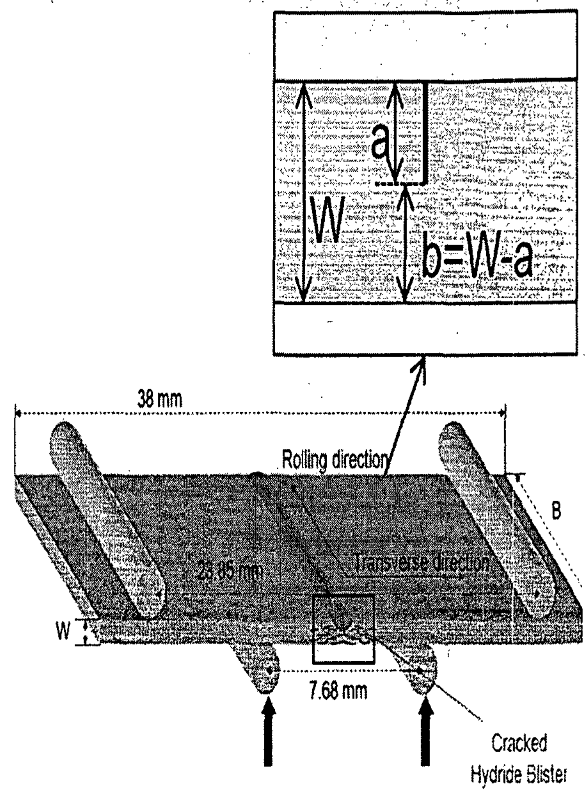
$$\boxed{RHF = 0.5 \times MHC + OHC}$$

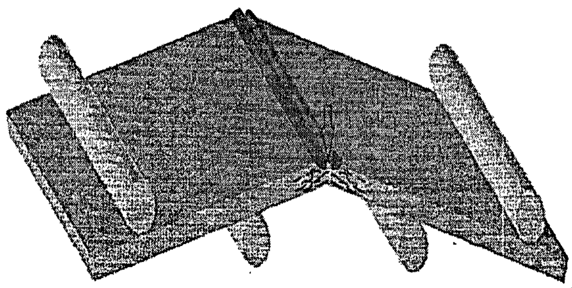


Fracture Toughness Testing

- 4-point bending
- Fatigue pre-cracking
- Electrical potential drop
- ➢ Load-displacement and crack growth curves







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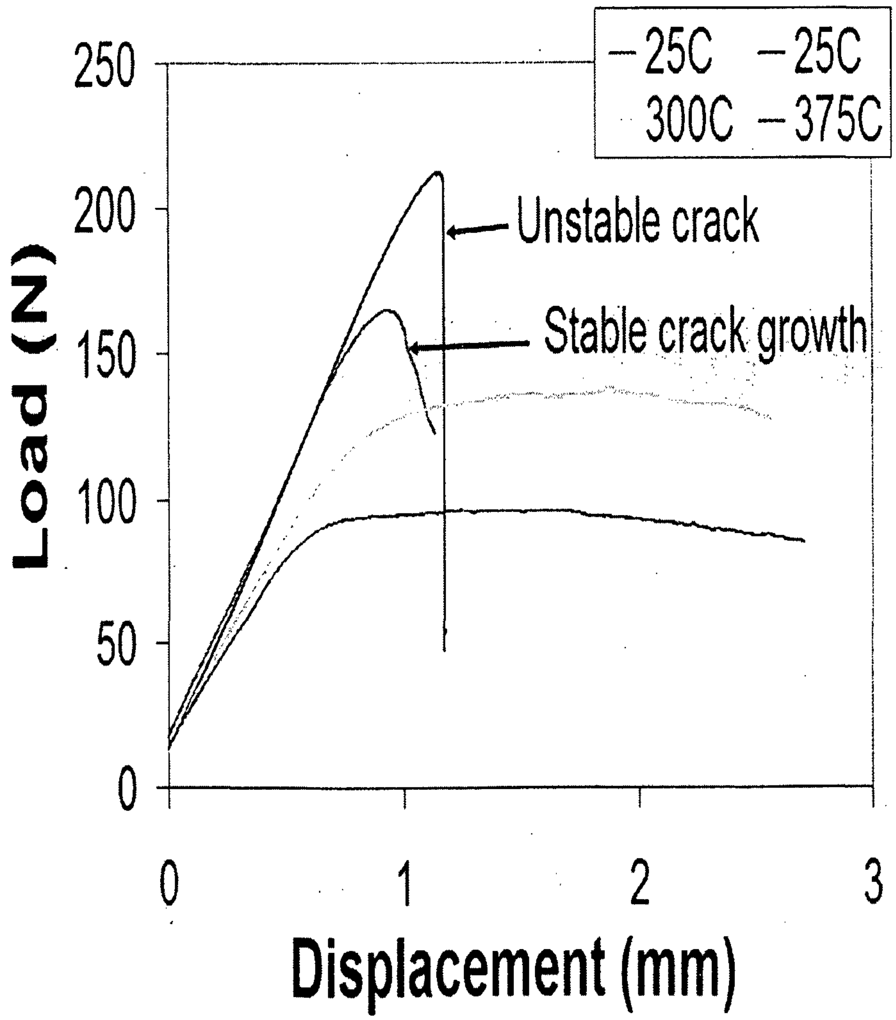
Load-Displacement and Crack Growth Behavior

- At 25°C load decrease occurs
  - Stable crack growth: gradual
  - Unstable crack growth: abrupt drop
- At 300°C and 375°C
  - Large plastic deformation plateau near maximum load
  - Crack tip blunting



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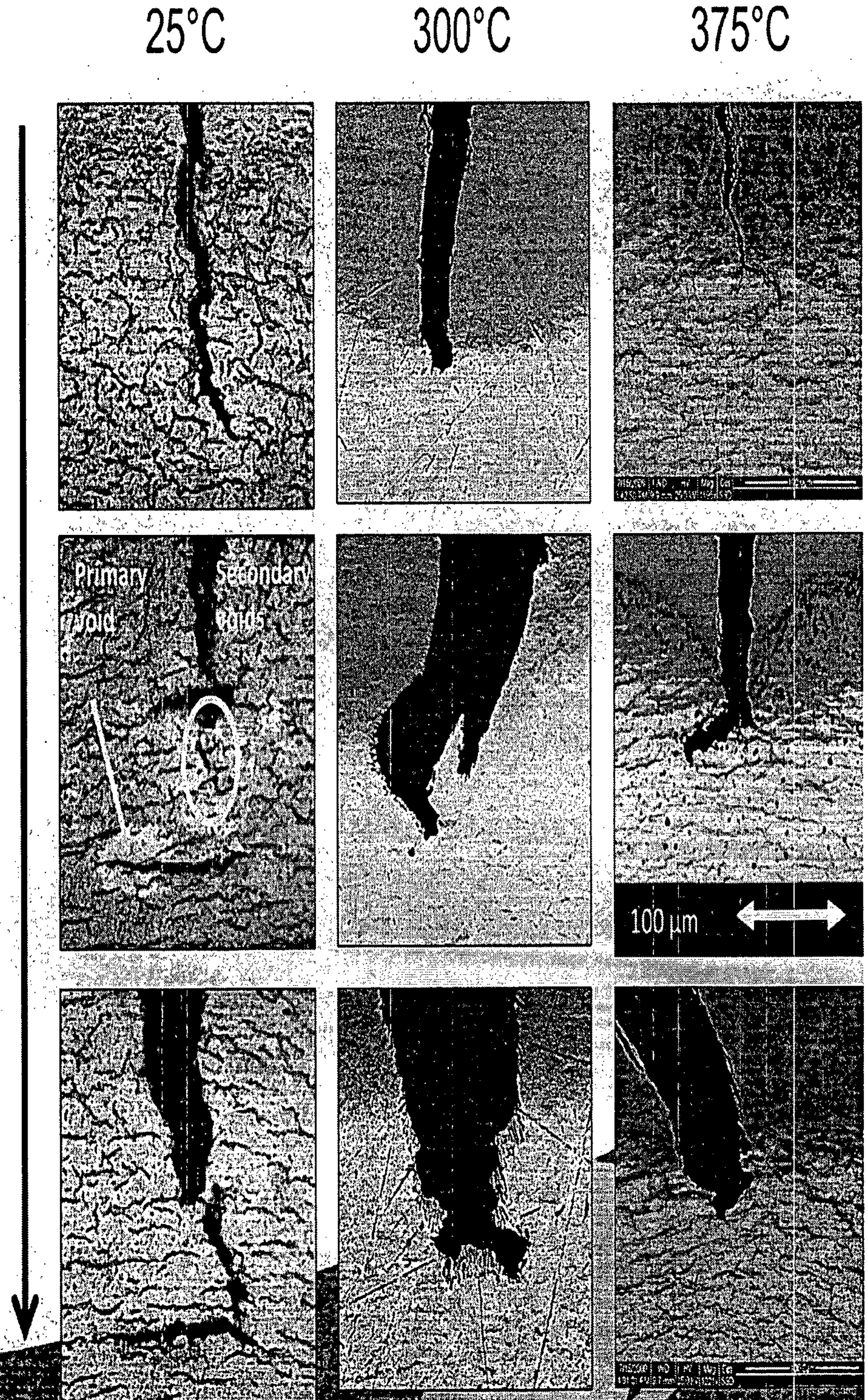
Fracture Behavior

- Hydride assisted cracking at 25°C
- Large crack opening with little crack extension at 300°C and 375°C
  - Crack tip blunting
  - Failure expected to occur by shear instability as observed previously
  - No obvious role of hydrides



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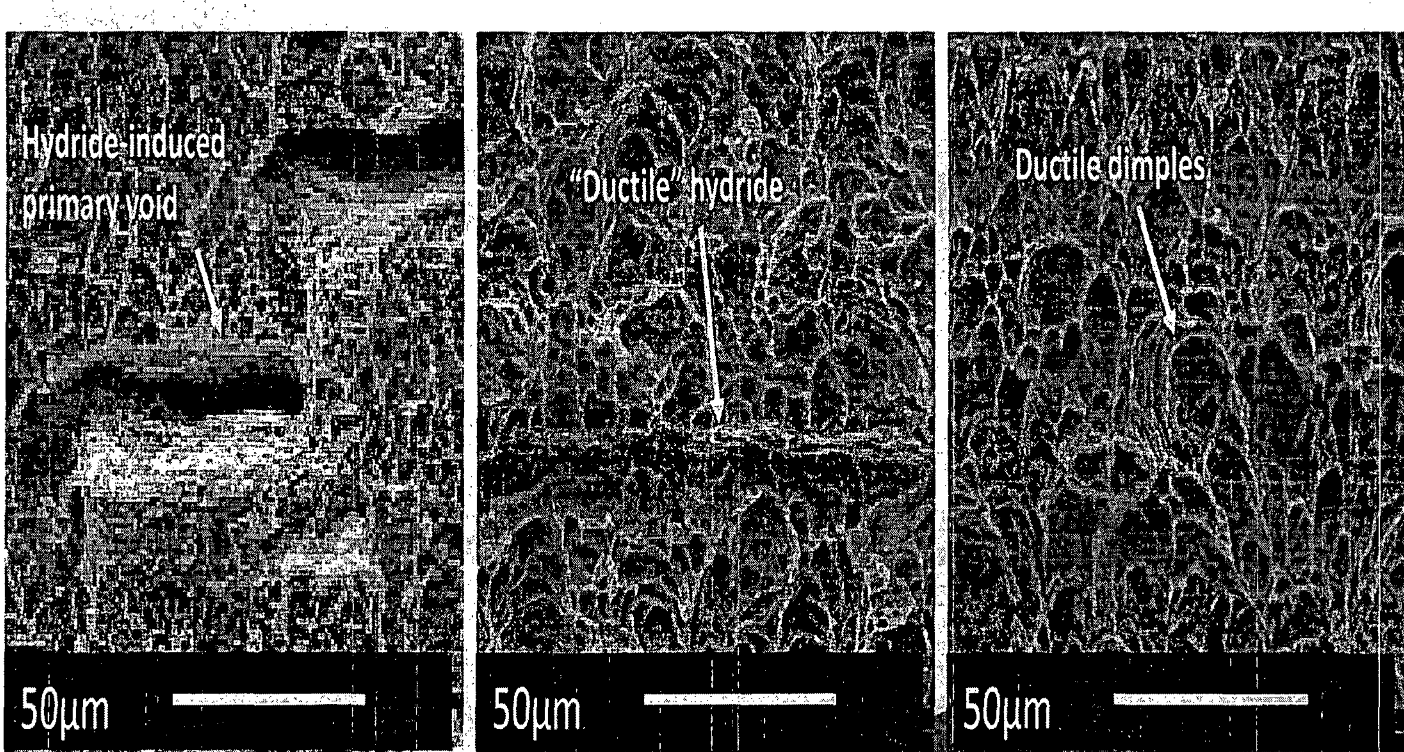
SEM Fractography

- Confirms metallographic observations
- At 25°C: hydride-induced primary voids linked by ductile failure
- At 300°C: ductile failure, ridges observed ('ductile' hydrides?)
- At 375°C: ductile failure, very large ductile dimples

25°C 300°C 375°C



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Fracture Mechanics

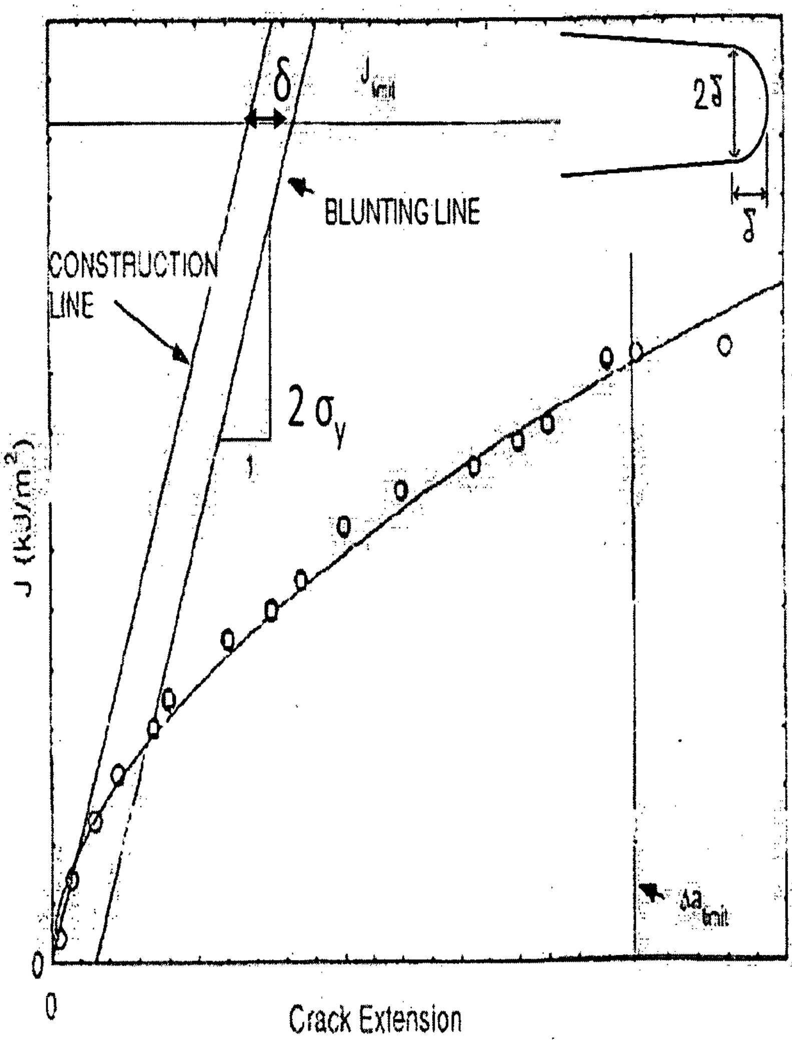
- Elastic-plastic fracture mechanics

$$J_{tot}^{i} = J_{el}^{i} + J_{pl}^{i} = \frac{K_i^2 \cdot (1-\nu^2)}{E} + J_{pl}^{i} \longrightarrow K_J^i = \sqrt{\frac{J_{tot}^{i} E}{(1-\nu^2)}}$$

$$J_{pl}^{i} = \left[J_{pl}^{i-1} + \left(\frac{\eta}{b_{i-1}}\right)\left(\frac{A_{pl}^{i} - A_{pl}^{i-1}}{B}\right)\right]\left[1-\gamma\frac{a_i - a_{i-1}}{b_{i-1}}\right]$$

B: specimen width
b=*W*-*a*, with *W* the specimen thickness
a: crack length
Apl: plastic energy spent by the applied load

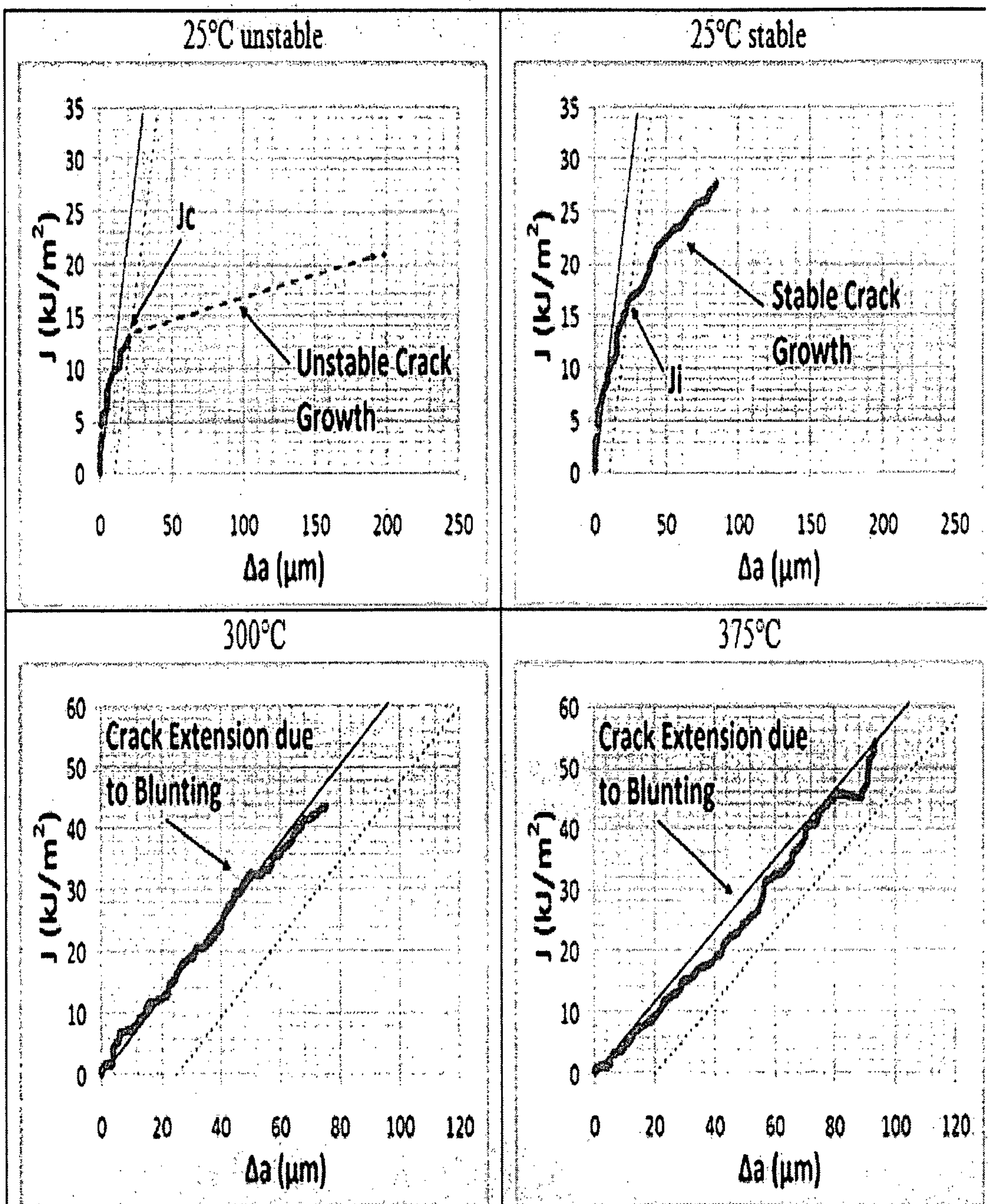
- J-R curves generated
- Specimen-size dependent fracture toughness
  - thin-wall cladding behavior
- Finite element modeling used to 'fine-tune' the elastic-plastic fracture mechanics analyses
  - Cast3M and Franc3D



Typical J-R Curves

- Crack growth observed at 25°C

- Only blunting observed at 300°C and 375°C



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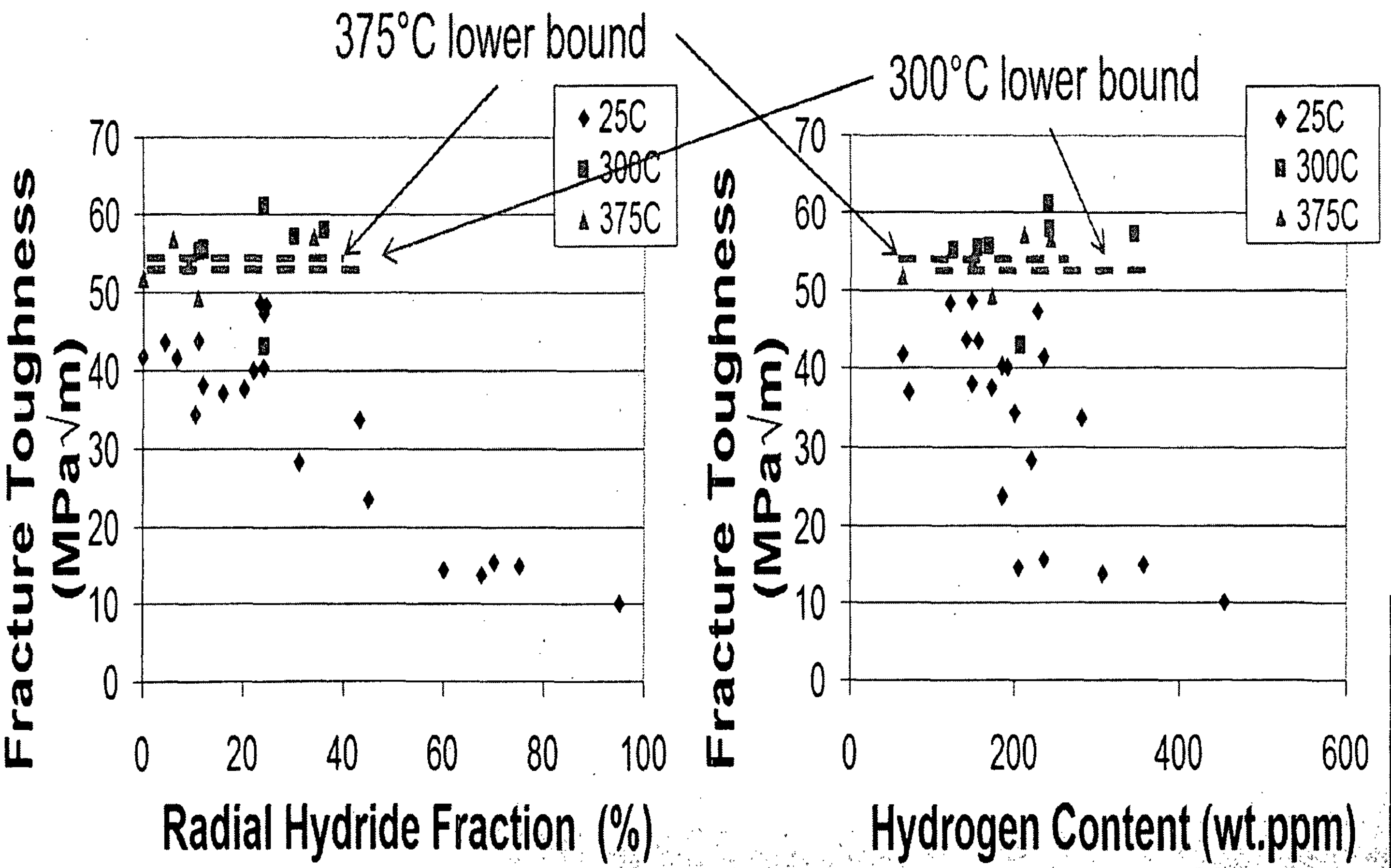
Influence of Hydrogen and Temperature

- Strong decrease in fracture toughness above 20% radial hydrides and 200wt.ppm hydrogen at 25°C
- Little or no influence of radial hydride fraction and hydrogen content at 300°C and 375°C within the range tested



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Conclusions

Fracture toughness of unirradiated **thin-sheet CWSR Zircaloy-4** was investigated for conditions of **through-thickness crack growth**, as a function of the **hydride microstructure** and at temperatures of **25°C, 300°C and 375°C**

- New experimental procedure
  - New hydriding procedure
  - Through-thickness crack growth in thin sheet
- Local characterization of hydride microstructure
  - Hydrogen content and hydride orientation
  - Microstructure gradient
- Elastic-plastic fracture mechanics
  - Fine tuned with finite element modeling
  - J-R curves produced

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Conclusions

- At 25°C, the fracture toughness and fracture process influenced by the hydride microstructure
  - Decrease from ~45MPa√m to ~10MPa√m with increasing hydrogen content and radial hydride fraction
  - Crack growth process controlled by formation of hydride-induced primary voids
- At 300°C and 375°C, the material is very resistant to the initiation of stable crack growth
  - Crack extension due to large amounts of crack-tip blunting
  - Failure would occur by shear instability
  - No cracking of hydrides and no effect of hydrides on fracture process
  - Toughness independent of hydride microstructure
  - K_J > 50 MPa√m at 300°C and K_J > 52 MPa√m at 375°C

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Thank you for your attention

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Backup Slides

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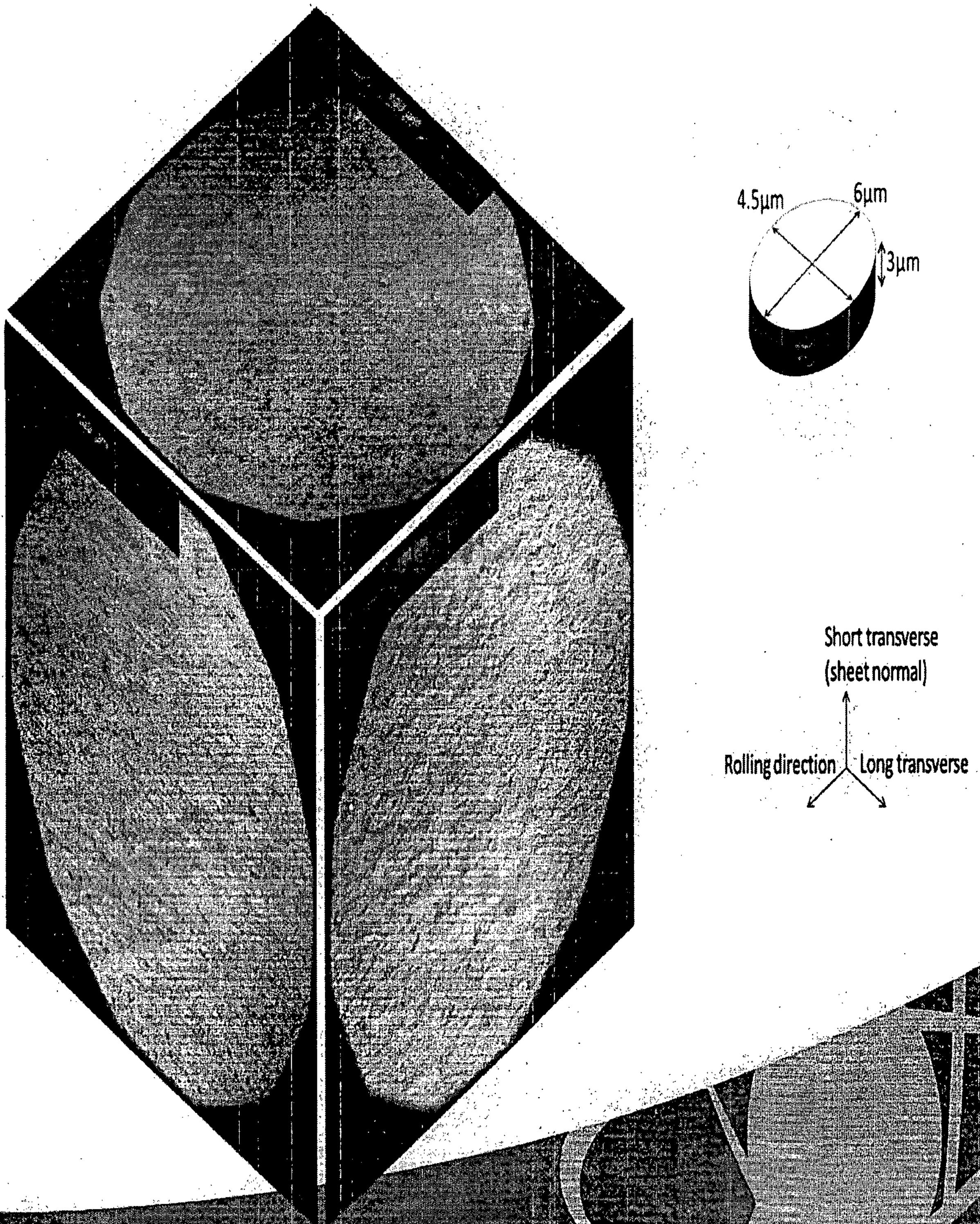
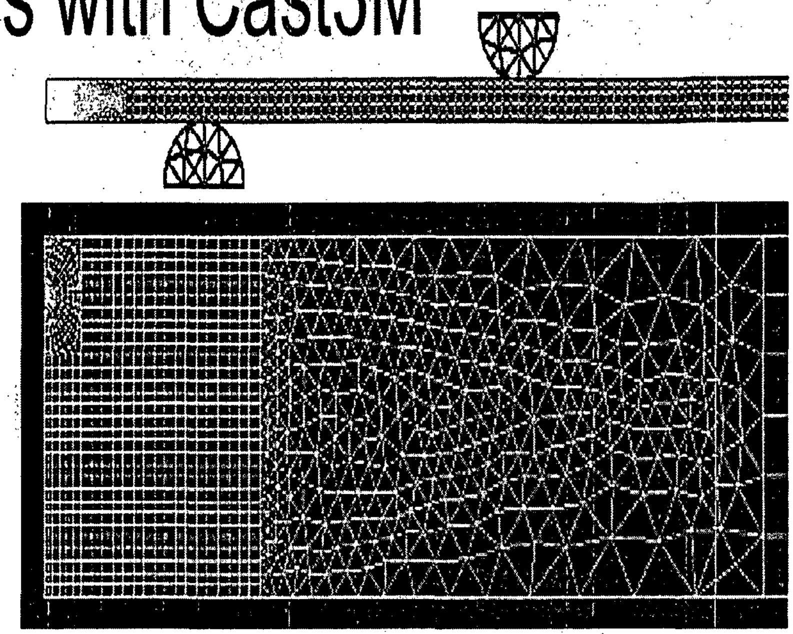
Grain Structure



Fracture Toughness Calculations with Cast3M

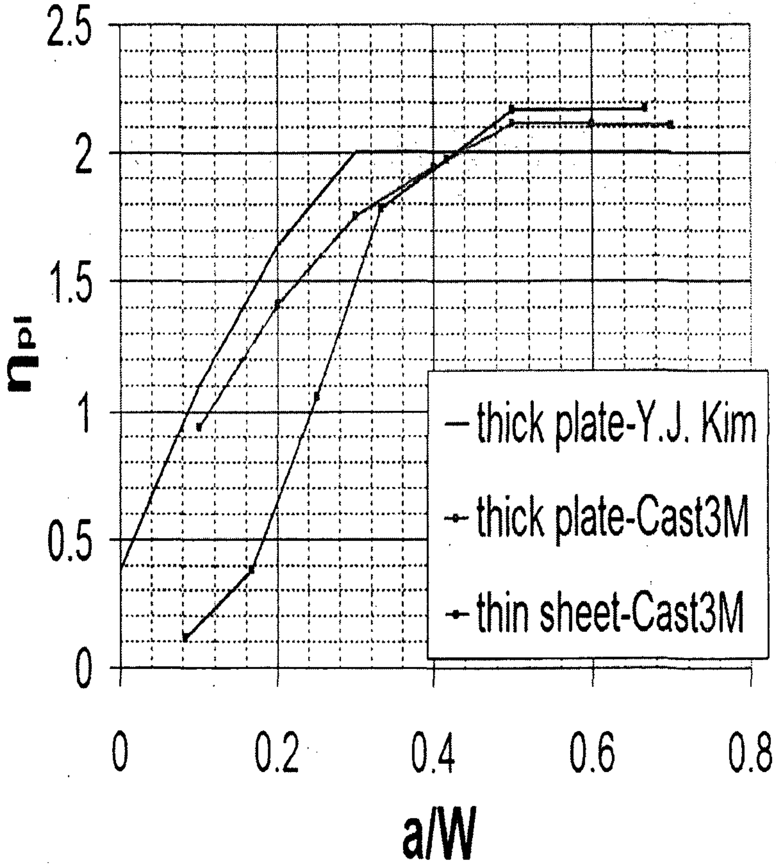


- 2D quadratic mesh
- Spider-web crack tip
- J-integral is dependent on the η_{pl} parameter

$$J_{tot} = J_{el} + J_{pl} = \frac{K^2 \cdot (1-\nu^2)}{E} + \frac{\eta_{pl} A_{pl}}{b \cdot B_n}$$

- Results different from thick specimen geometries

$$\eta_{pl} = \frac{\partial J_{pl}}{\partial \left(A_{pl} / b \cdot B \right)}$$



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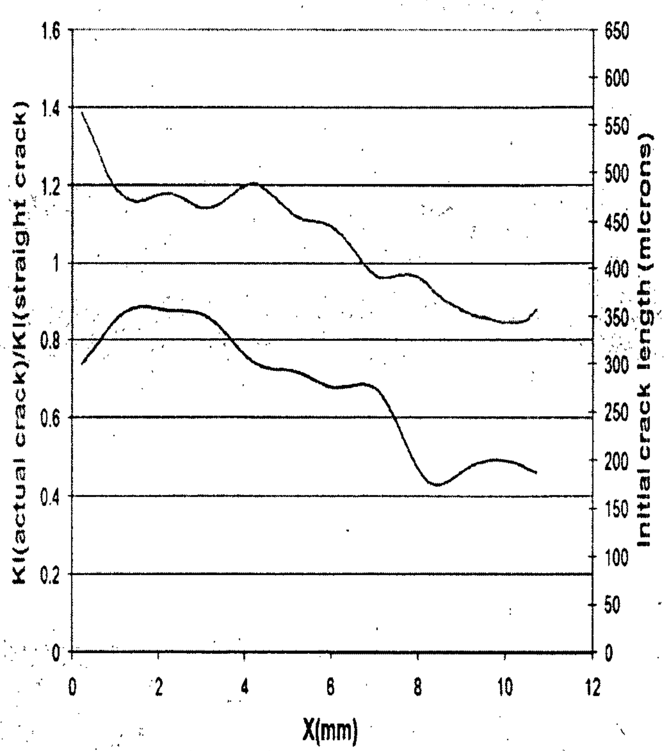
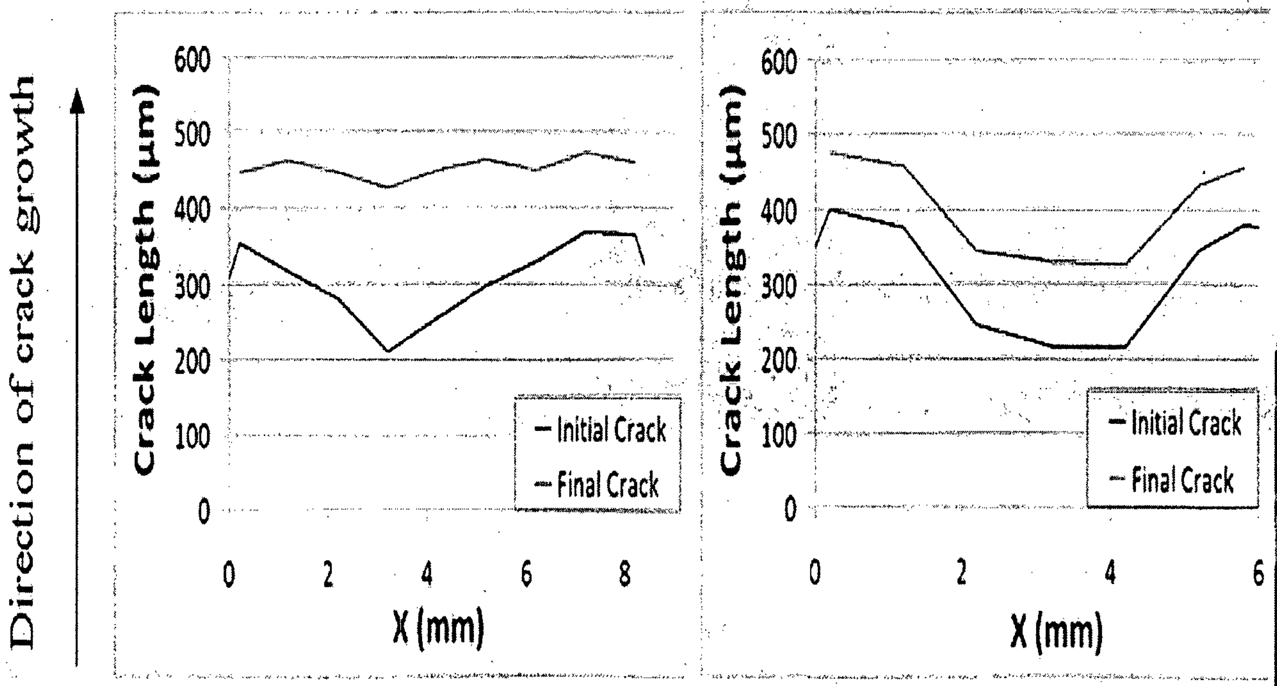
Modeling of Uneven Cracks with Franc3D

- Elastic fracture mechanics modeling of uneven cracks
- The fracture toughness is lowest where the cracks were the shallowest
- Shallowest portions of the crack front advance first at 25°C
- Crack front advances uniformly at 300°C and 375°C





25°C

300°C or 375°C (similar behavior)