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Regulators Participation in IAC/ZIRP: Proposed Use of Zorita Internals Materials for Research

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NRC's Related Activities and Perspective

- **Testing, evaluation & research on irradiated stainless steels**
- **Investigation of degradation of BWR internals**
- **Investigation of degradation of PWR internals**
- **Primary areas of interest to NRC**
- **Proposed NRC test matrix for Zorita Internals Research Project (ZIRP)**

Primary Research Areas

- **Materials at a series of low doses to understand thresholds for irradiation degradation:**
  - **Fracture and tearing toughness,**
  - **Irradiation-Assisted Stress Corrosion Cracking**
- **Materials at a series of high doses to understand if saturation of irradiation degradation of mechanical properties occurs:**
  - **Radiation-induced segregation**
  - **Void swelling, fracture and tensile properties**
  - **Characterization of deformation at high fluences**

Historical Background

- José Cabrera NPP (Zorita NPP) was shutdown April 30th 2006.
- UNION FENOSA, owner of Zorita NPP, has offered to the CEIDEN (Spanish Strategic Committee on Nuclear R&D) materials of potential interest for R&D.
- CEIDEN offers materials from Zorita to organizations, labs, R&D programs, etc.
  - Synergy among different recipients will be useful to reduce the cost of material harvesting
  - Comparison of results obtained by different labs will also be of great interest for the nuclear community
- CSN, member of CEIDEN, took the initiative of making a proposal to launch a cooperative research project under the Nuclear Energy Agency umbrella
- Committee for the Safety of Nuclear Instillations First Meeting on Zorita was in 2006

Actions Undertaken

- CIEMAT, on behalf of CEIDEN, prepared a revised detailed technical proposal including:
  - Test matrix
  - Fluences and temperature estimations were prepared by an engineering consultant, under Spanish CEIDEN requirements
- Detailed technical proposal, dated February 2007, was sent to the Nuclear Energy Agency (NEA) at the beginning of March 2007 and forwarded by the Working Group on Integrity of Components and Structures (IAGE) secretariat to member delegates and organizations
- A second experts meeting was held the June 1st 2007 at NEA premises

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Core Internals Components

Form	Material	Thickness	Irradiation
Baffle plates	304 SS Annealed Hot Rolled & Pickled	≈ 2.85 cm	Up to 58 dpa
Baffle/former bolts	347 SS		Up to 58 dpa
Formers	304 SS Annealed Hot Rolled & Pickled	≈ 4 and 6 cm	
Core barrel	304 SS Annealed Hot Rolled & Pickled	≈ 4 cm	
Thermal shield	304		
Core barrel weld			1 dpa

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Project Objectives

- **The current database for irradiated stainless steels is insufficient to assess core internals components performance over the full range of radiation service exposures anticipated for LWRs and in particular for PWRs.**

- **The objective of this cooperative project is to generate high quality data to fill existing gaps and improve the mechanistic understanding to avoid inadequate extrapolations in the evaluation of core internals in both BWRs and PWRs.**

- **Materials from Zorita NPP are considered adequate to generate a database representative of the behavior of internals components in LWRs.**
    - **High thickness of baffle plates**
    - **Doses up to 58 dpa.**

- **Potential applications of the results of this program are:**
  - **Licensing purposes, Inspection programs, Lifetime management and Lifetime extension**

Proposed Project Scope

- **Tests with high and low dpa materials.**

- **Proposed testing and evaluation**
  - **Task 1. Material Documentation, Fluence and Thermal Evaluation.**
  - **Task 2. Examination of Baffle-Former Barrel Assembly before extraction**
  - **Task 3. Crack Growth Rate Tests**
  - **Task 4. Susceptibility to IASCC and Deformation Mode**
  - **Task 5. Fracture Toughness Determination**
  - **Task 6. Mechanical, Micro-structural and Micro-chemical Characterization**
  - **Task 7. Compilation of results and analysis**

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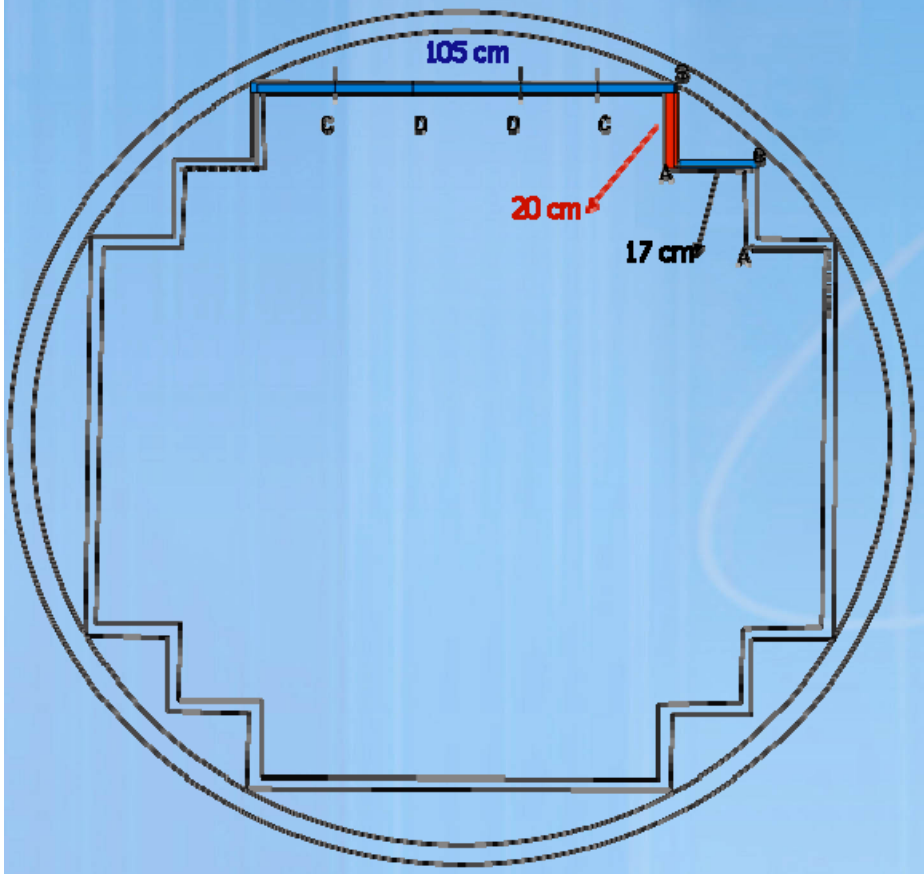
TASK 1. Material Documentation, Fluence and Thermal Evaluation

- **Unirradiated material property data need to be obtained from material certification sheets.**
- **Visual inspection, photographic records and dimensional measurements of removed material need to be performed**
- **Calculation of the irradiation and thermal histories of the removed materials using a three-dimensional time-dependant model of the reactor core need to be carried out:**
  - **gamma ray heat generation rates**
  - **fast neutron exposure parameters (E > 1.0 MeV and E > 0.1MeV)**
  - **neutron flux and fluence (dpa)**
- **This data will be used to correlate observed changes in material properties among the various samples and to calculate the operating temperatures of the samples.**

Baffle Configuration



ESTIMATION OF ACCUMULATED FLUENCES AND TEMPERATURES

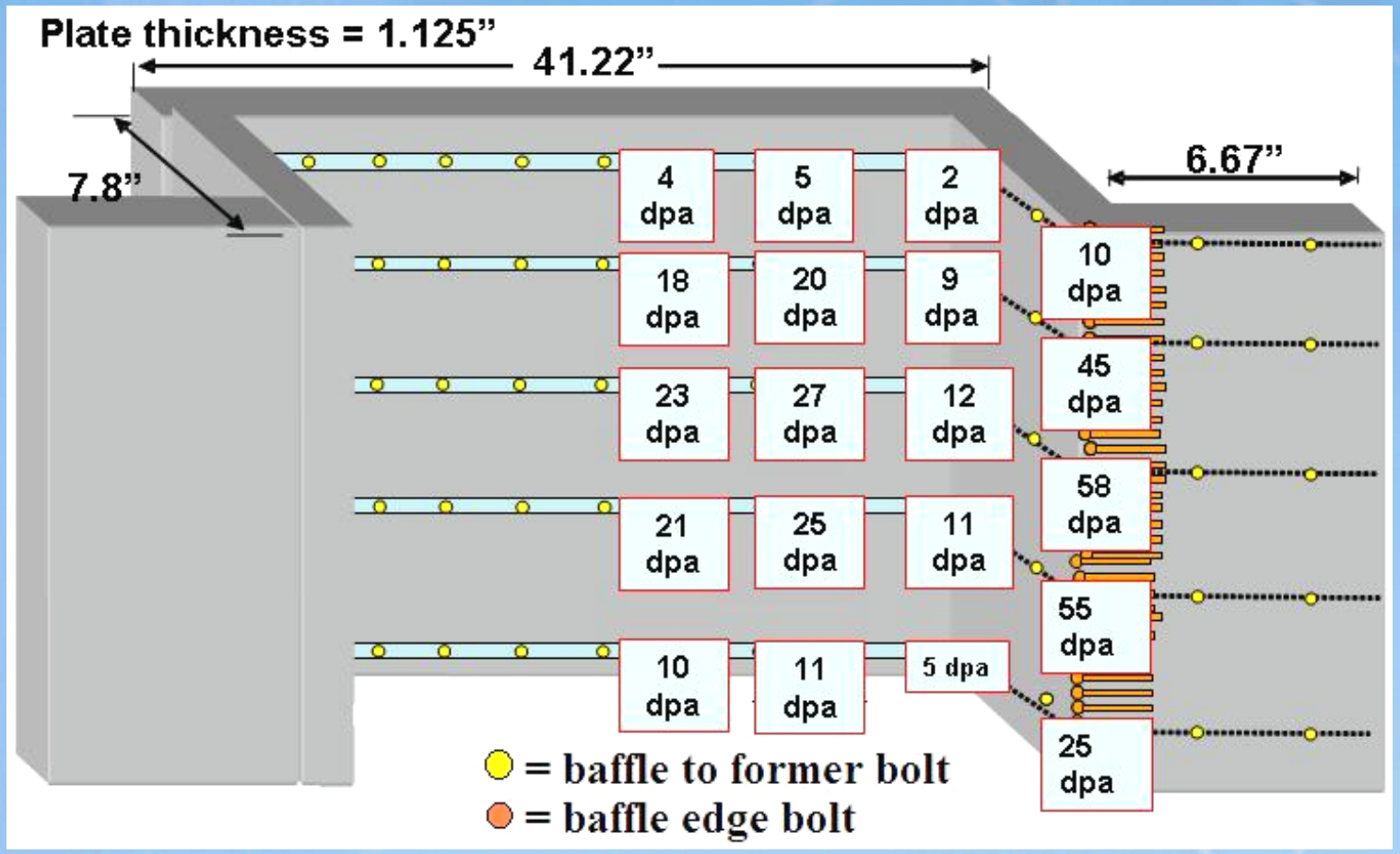
Baffle dose (dpa), internal surface				
Position	A	B	C	D
Former 1	10.35	2.09	4.70	4.38
Former 2	45.11	9.13	20.47	17.70
Former 3	58.39	11.91	26.50	22.91
Former 4	54.59	11.06	24.82	21.45
Former 5	24.87	5.03	11.29	9.76

Baffle dose (dpa), external surface				
Position	A	B	C	D
Former 1	6.48	1.31	3.37	3.14
Former 2	28.22	5.71	14.69	12.70
Former 3	36.53	7.39	19.02	16.44
Former 4	34.22	6.92	17.82	15.40
Former 5	15.56	3.15	8.10	7.00

Estimated T at the Occluded Areas of the BFB is ~ 350-355°C

Data About Fluence Levels and Temperatures of the Internals

Irradiation Schematic Representation



TASK 2.Examination of Baffle-Former Barrel Assembly before Extraction

- **Baffle-former-barrel assembly including plates and bolts may have undergone dimensional distortion induced by swelling and irradiation creep and relaxation of preload on bolts due to creep.**
  - **Visual and photographic examination of Zorita baffle-former-barrel assembly including plates and bolts in the area of interest and determine dimensional changes, and the torques of baffles bolts.**
  - **The examination of the areas (in and around) with highest dpa and highest temperature:**
    - **baffle re-entrant corners fabricated of 304 SS and associated bolts made of 347 SS.**

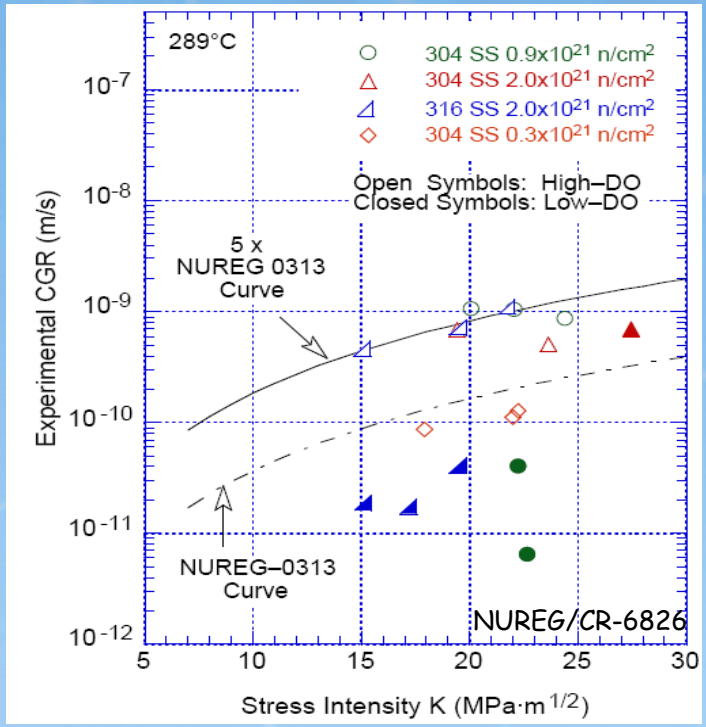
Task 3 – Crack Growth Rate tests

- The crack growth rate for irradiated stainless steels (0.53-2 dpa, E>1MeV) in NWC is a factor of x 5 higher than the disposition curve proposed in NUREG 0313 Rev 2 for sensitized austenitic SSs

- Hydrogen water chemistry (HWC) mitigates CGR for unirradiated material, but some CGR results obtained at a fluence of $9x10^{21}n/cm^2$ point out that the HWC is not effective at this fluence. (Jenssen 2003)

- On the other hand, very little environmental enhancement of crack growth rate in normal water chemistry (NWC) has been observed in 304 SS irradiated to $0.3x10^{21}n/cm^2$ (Chopra 2003)

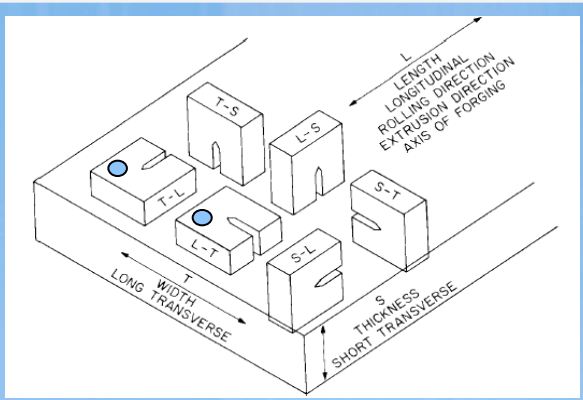
- CGR data in PWR conditions for irradiated materials with high dose typical of this type of reactor are very scarce.

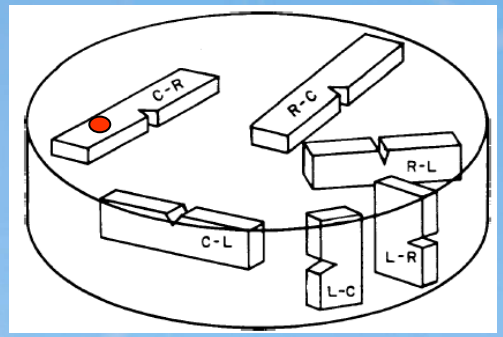


Task 3 – Crack Growth Rate tests

- New CGR data are needed to
  - Establish the effectiveness of HWC to mitigate crack propagation at fluences higher that 3 $x10^{21}$ n/cm^2(4 dpa) and to increase the database at lower doses in HWC conditions.
  - Identify the "fluence threshold" for the existence of environmental cracking to distinguish between IGSCC and IASCC in BWR conditions, doses around 0.2-0.5 $x10^{21}$ n/cm^2 (0.3-0.7dpa)
  - Establish curves of CGR as a function of dpa in a large range of representative conditions to the end of PWR life
  - Assess the K value ASTM validity criteria.

Task 3 – Crack Growth Rate tests





- 1CT and ½ CT specimens of 304 SS, and RCT of 347.
- In T-L orientation, the crack growths in the direction of the plate long axis and parallel to the rolling direction.
- In L-T, perpendicular to the plate long axis and parallel to the rolling direction

➤ Different specimen size to asses the application of ASTM validity criteria to SCC testing of irradiated SS.

➤ High dose irradiated stainless steels show peculiar strain hardening characteristics, with strain softening at higher fluencies

⇒ The plastic deformation in irradiated SS can be larger than predicted when taking into account the increase of the yield strength.

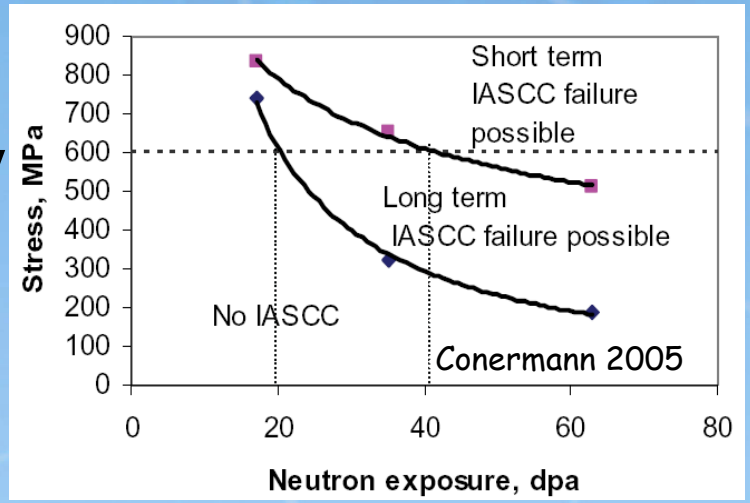
➤ Higher crack growth rates have been reported where K-size criteria are violated in crack growth testing of irradiated stainless steels.

➤ At least two or three specimens per condition (water chemistry, K value, etc), at least for the lower dose, are suggested in order to *reduce data scattering*.

TASK 4. Susceptibility to IASCC and Deformation Mode

- The availability of predictive curves of IASCC failure is of interest for predicting the life of internal components.

- The determination of the influence of key parameters (irradiation dose, T, stress, strain rate, material, and deformation mode) in the response to IASCC of irradiated stainless steels is needed for modelling this process

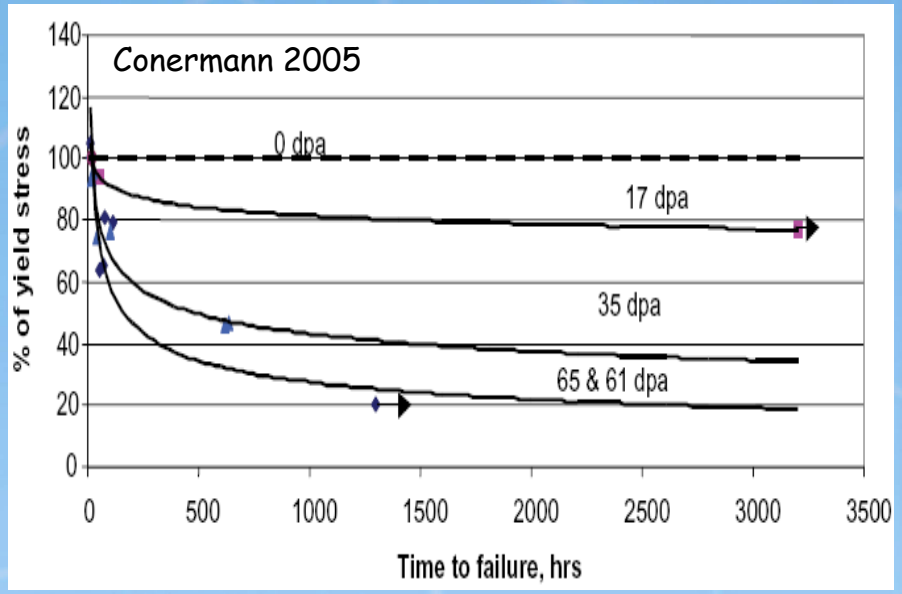


- Deformation characteristics of LWR-irradiated stainless steels and their influence on the IASCC behavior remain unclear because little research work has been done with PWR internals material.

TASK 4. Susceptibility to IASCC and Deformation Mode

New failure time data are needed to:

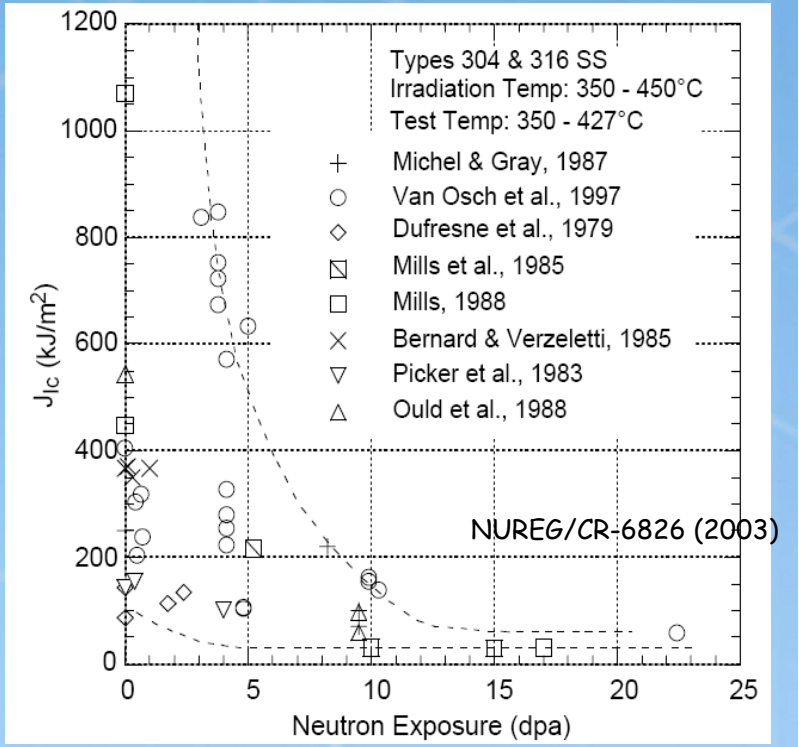
- **Extend predictive curves to a range of dpa representative of PWR extended operation**
- **Establish an IASCC parametric model applicable to PWRs**



Consider SCC susceptibility tests such as SSRT and constant load tests in high temperature water and in inert environment.

TASK 5. Fracture Toughness Determination

- Fracture Toughness of irradiated material decreases with dose reaching the minimum value around 5 dpa, and a saturation value at around 10 dpa.



- Data from different heats with the same dose show a significant scatter that could strongly penalize structural integrity assessments when using the more conservative curve.

- The failure mode changes from dimple fracture to channel fracture as a function of dose.
- Void swelling can have a relevant influence in fracture toughness

TASK 5. Fracture Toughness Determination

- New Fracture Toughness data are needed to:
  - Define the transition to lower fracture toughness at fluences between 2 and 5 dpa.
  - Identify possible transition from ductile to channel fracture due to irradiation at a high dpa range
  - Identify material and orientation influence in the fracture toughness data
  - Determine influence of temperature in the fracture mode
  - Determine the influence of water in fracture toughness

TASK 6. Mechanical, Micro-structural and Micro-chemical Characterization

- Knowledge of the evolution of the mechanical, micro-structure and micro-chemistry of the materials tested in the previous tasks is needed for the interpretation of the results and for the formulation of mechanisms.

- In principle, specimens from bolts (347 SS) and baffle plates (304 SS) located at areas of higher temperature and higher fluence could provide useful information on swelling of both materials.
  - A temperature of around 350ºC has been estimated at the re-entrant corners of the baffle former assembly as a consequence of the gamma heating.

TASK 7. Compilation of Test Results and Final Document Preparation

- At the end of the testing
  - ➔Technical follow up meeting is called for
- At that meeting test results from all the laboratories are to be collected & compiled
- The compiled test results will be available to all members
- A project final report will be generated incorporating all the experts comments on the test results.
  - ➔Analysis is to be conducted independently between regulators and industry
- The final report will be distributed to all members.

Phases of the Project

- **The Project will have two phases:**
- **Phase 1:**
- **Harvesting, task 1 and task 2**
  - **Task 1:Material documentation, detailed fluence and thermal evaluation.**
  - **Task 2: Visual examination of baffle- former barrel assembly before extraction; torque measurement of bolts**
- **Phase 2:**
- **All other tasks 3 to 7 – Characterization and testing**
- **Transportation (to and from)**
- **Storage of the test coupons**

Phase 2: NRC Proposed Test Matrix

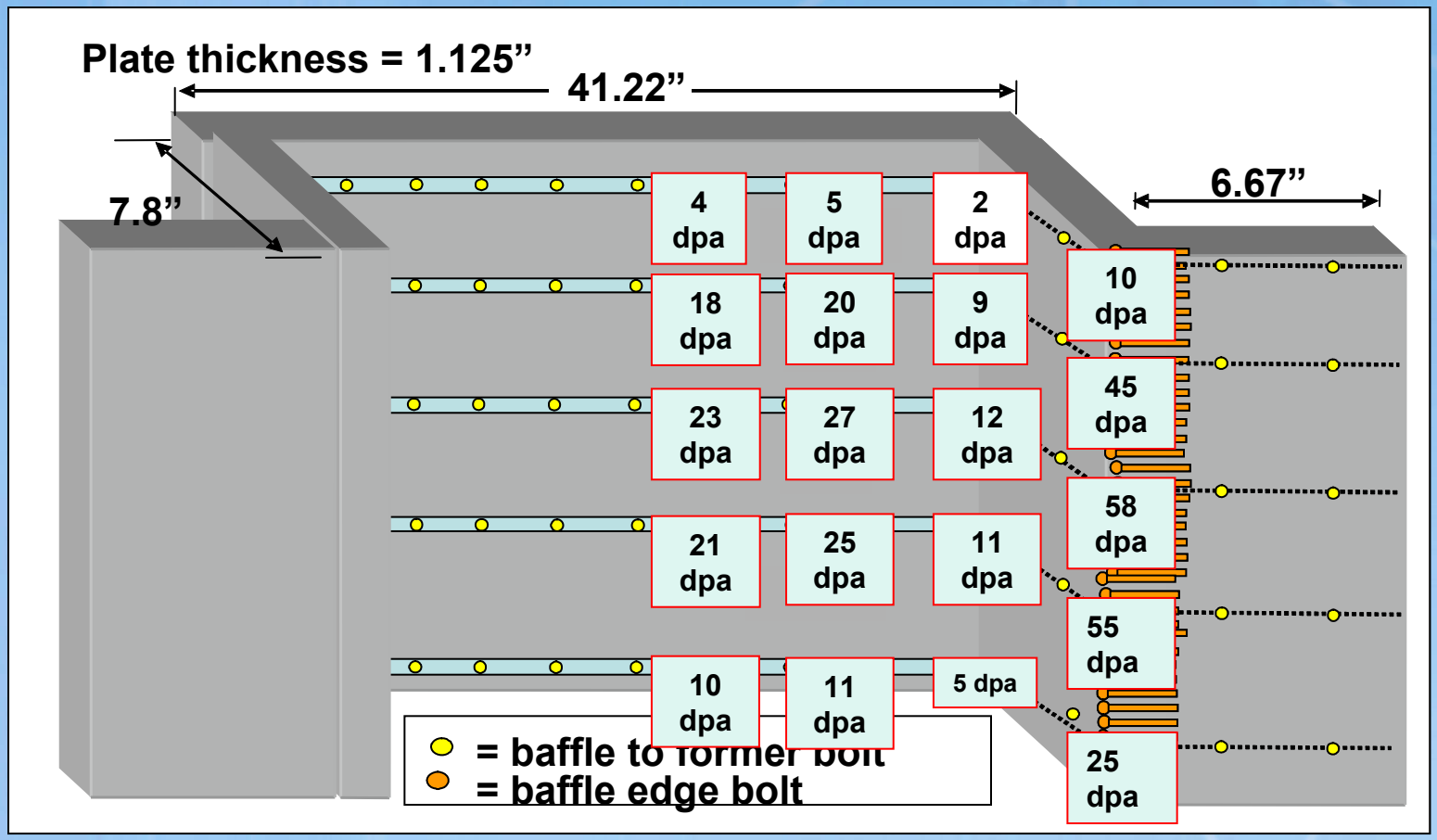
- <u>Phase 2: Tasks 3 to 7</u>
- Task 3. Crack growth rate (CGR) tests
- Task 4. Susceptibility to IASCC and deformation mode
- Task 5. Fracture toughness determination
- Task 6. Mechanical, micro-structural and micro-chemical characterization
- Task 7. Compilation of results and analysis

Priorities Defined by NRC & CSN

- NRC and CSN developed test Matrix
  - ➔ Analyzed the existing data
  - ➔ Based on the analysis, identified the potential use of information from testing the Zorita materials
- Participants in the project may express their priorities.
- New tests can still be proposed at this stage
- The final technical proposal & tests matrix will be prepared by all participants in the project

Data About Fluence Levels and Temperatures of the Internals

Irradiation Schematic Representation



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Task 3.1: CGR Tests in PWR Environment at 320°C

Material	Specimen Type*	Fluence (dpa)	K Range MPa $m^{1/2}$	Specimens	Objective
Baffle Plate/304	1/4-T CT	≈5	5-20	2 (M)	Effect of fluence
Baffle Plate/304	1/4-T CT	≈8	5-20	2 (H)	Effect of fluence
Baffle Plate/304	1/4-T CT	≈11	5-20	2 (H)	Effect of fluence
Baffle Plate/304	1/4-T CT	15-25	5-20	2 (H)	Effect of fluence
Baffle Plate/304	1/4-T CT	> 25	5-20	2 (H)	Effect of fluence
Bolt: 347SS	1/4-T CT	≈5	5-20	2 (M)	Effect of fluence
			Total:	12	

Task 3.2: Tests in BWR Environments (NWC & HWC) at 290°C

Material	Specimen Type*	Fluence (dpa)	K Range MPa $m^{1/2}$	Specimens	Remarks
Baffle Plate/304	1/4-T CT	≈3	5-20	2 (H)	Effectiveness of HWC
Baffle Plate/304	1/4-T CT	≈5	5-20	2 (H)	Effectiveness of HWC
Baffle Plate/304	1/4-T CT	15 - 25	5-20	2 (H)	Effectiveness of HWC
Core Barrel/304	1/4-T CT	≈0.5	5-20	2 (M)	Validate threshold fluence
Bolt: 347SS	1/4-T CT	≈3	5-20	2 (M)	Validate threshold fluence
			Total:	10	

* Also consider 0.4-T CT specimens (M)

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Task 4.1: SSRT Tests in PWR Environment at 320°C

			Number of Specimens		
Material	**Specimen Type**	**Fluence (dpa)**	**PWR Water**	**High T Air**	**Remarks**
Baffle Plate/304	Flat dog bone	≈58	2 (M)	1 (L)	Effect of fluence
Baffle Plate/304	Flat dog bone	≈25	2 (M)	1 (L)	Effect of fluence
Baffle Plate/304	Flat dog bone	≈10	2 (M)	1 (L)	Effect of fluence
		Total:	6	3	

Task 4.2: SSRT Tests in BWR Environments (NWC & HWC) at 290°C

			Number of Specimens			
Material	**Specimen Type**	**Fluence (dpa)**	**NWC**	**HWC**	**High T Air**	**Remarks**
Baffle Plate/304	Flat dog bone	15 - 25	2 (M)	2 (M)	1 (L)	Effect of fluence
Baffle Plate/304	Flat dog bone	≈5	2 (M)	2 (M)	1 (L)	Effect of fluence
Baffle Plate/304	Flat dog bone	≈3	2 (M)	2 (M)	1 (L)	Effect of fluence
Core Barrel/304	Flat dog bone	≈0.5	2 (L)	2 (L)	1 (L)	Effect of fluence
		Total:	8	8	4	

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Task 5. Fracture Toughness Determination

			Number of Specimens				
Material	Specimen Type*	Fluence (dpa)	Air Room T	Air High T	Water Tran.	Water Long.	Remarks
Baffle Plate/304	1/4-T CT	≈3	1 (L)	1 (L)	2 (M)	2 (L)	Effect of fluence
Baffle Plate/304	1/4-T CT	≈5	1 (L)	1 (M)	2 (H)	2 (L)	Effect of fluence
Baffle Plate/304	1/4-T CT	≈8	1 (M)	1 (M)	2 (H)	2 (M)	Effect of fluence
Baffle Plate/304	1/4-T CT	≈25	-	1 (M)	2 (M)	-	Effect of fluence
Baffle Plate/304	1/4-T CT	≈50	-	1 (M)	2 (M)	-	Effect of fluence
Core Barrel Weld	1/4-T CT	≈1	1 (L)	1 (M)	2 (M)	-	Effect of material
Core Barrel Weld	1/4-T CT	≤0.1	1 (L)	1 (L)	2 (L)	-	Threshold
	Total:		5	7	14	6	

* Also consider 0.4-T CT specimens (M)

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Task 6.2: Ball Punch Tests

Material	Specimen Type	Fluence (dpa)	Specimens	Remarks
Baffle Plate/304	3 x 0.25 mm disk	≈58	2 (L)	Effect of fluence
Baffle Plate/304	3 x 0.25 mm disk	≈25	2 (L)	Effect of fluence
Baffle Plate/304	3 x 0.25 mm disk	≈8	2 (L)	Effect of fluence
Baffle Plate/304	3 x 0.25 mm disk	≈5	2 (L)	Effect of fluence
		Total:	8	

Task 6.3: Micro-structural and Micro-mechanical Tests

Material	Specimen Type	Fluence (dpa)	Specimens	Remarks
Baffle Plate/304	3 x 0.25 mm disk	≈58	3 (H)	Void Swelling microst. defects
Baffle Plate/304	3 x 0.25 mm disk	≈25	3 (H)	Void Swelling microst. defects
Baffle Plate/304	3 x 0.25 mm disk	≈8	3 (H)	Void Swelling microst. defects
Baffle Plate/304	3 x 0.25 mm disk	≈5	3 (H)	Void Swelling microst. defects
		Total:	12	

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Projected Testing Cost

Task	Type of Test	High Priority	Medium Priority	Low Priority
Task 3.1	CGR in PWR	24	12	--
Task 3.2	CGR in BWR	15	5	--
Task 4.1	SSRT in PWR	--	6	3
Task 4.2	SSRT in BWR	--	12	8
Task 5	J-R in air	--	6	6
	J-R in water	4	10	6
Task 6.2	Ball punch	--	--	2
Task 6.3	TEM	12	--	--
	Cost	2.2M	2.2M	1.0M
	Total Cost	5.4M		

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Test Schedule

	Year 1				Year 2				Year 3				Year 4			
Quarters:	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
CGR test system																
Task 3.2 *	----	----	----	----	----	----	----	-X								
Task 3.1 *							---	----	----	----	----	----	----	----	----	--X
JR test system																
Task 5 (Air)	----	----	----	----	----	----	--X									
Task 5 (Water)							---	----	----	----	----	----	----	----	----	--X
SSRT test system																
Tasks 4.1/4.2 Air	----	--X									----	--X				
Task 4.2			----	----	----	----	----	----	----	--X						
Task 4.1													----	--X		
TEM Examination																
Task 6.3	----	----	----	----	--X											
Ball Punch																
Task 6.2						----	----	--X								

*** Schedule covers high priority tests only**

Deliverables and Applications

- The deliverables will be the results of the tests performed
  - ➔ The test results to be shared among participants
  - ➔ The analysis of the test results
    - ➢ Independently performed by individual members

- Potential applications are up to each participant
  - ➔ Envisaged potential applications:
    - ✓ Licensing purposes
    - ✓ Inspection programs
    - ✓ Lifetime management
    - ✓ Lifetime extension
    - ✓ Exchange of experiences and knowledge (an added value of projects of this kind)

Other Considerations

Sample disposal

- Once the tests have been performed, the samples can be sent back to the utility or be disposed by the laboratories in its/their respective countries.
- Only the harvesting cost of this activity is to be included in the project.

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Summary

- **The internals will be available in the first quarter of 2011**
- **However, some Task 1 activities (documentation) must start in 2009**
  - **NRC has allocated some budget for 2009**
- **NRC has developed a test matrix based on the technical specification prepared by CIEMAT and on the discussions held during the two experts' meetings held at NEA**
- **Changes in the test priorities or new proposals will be considered.**

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- **Participants in the Project ➤ From regulators**
  - **➔ Firm commitment ➔ NRC, CSN**
- **New Proposal ➤ We (NRC & CSN) regulators**
  - **➔ Join as individual participants with industry**
  - **➔ Need to negotiate cost of participation**

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NRC Questions

- What will be the spending plan?
  - ➔ 2009 costs
  - ➔ 2010 costs
  - ➔ 2011 costs
- NRC has anticipated expenditures in 2009 and 2010.
- What are the contract specifics for this project?
  - ➔ Contract managed by IAC?
    - – NRC establishes a Memo of Understanding with the IAC ?
  - ➔ Contract with the decommissioning agency?
    - – NRC contracts with the decommissioning agency?