

CIR II Program: Description of the Boris 6 and 7 Experiments in the BOR-60 Fast Breeder Reactor

Technical Report

CIR II Program: Description of the Boris 6 and 7 Experiments in the BOR-60 Fast Breeder Reactor

1011787

Final Report, August 2005

EPRI Project Manager
R. Pathania

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

EDF – Electricité de France

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2 or internally x5379, (925) 609-9169, (925) 609-1310 (fax).

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2005 Electric Power Research Institute, Inc. All rights reserved.

CITATIONS

This report was prepared by

EDF – Electricité de France
Site Des Renardieres
Avenue Des Renardieres – Ecuelles
F-77818 Moret Sur Loing Cedex
France

Principal Investigators
J.P. Massoud – EDF
P. Dubuisson – CEA/SRMA
P. Scott, Framatome – ANP
V.K. Chamardine – RIAR

This report describes research sponsored by the Electric Power Research Institute (EPRI).

The report is a corporate document that should be cited in the literature in the following manner:

CIR II Program: Description of the Boris 6 and 7 Experiments in the BOR-60 Fast Breeder Reactor. EPRI, Palo Alto, CA: 2005. 1011787.

REPORT SUMMARY

Irradiation-assisted stress corrosion cracking (IASCC) can impact highly irradiated light water reactor (LWR) internals located very close to the core. This study on BOR-60 irradiations of commercial and experimental alloys is an essential step in characterizing the effect of neutron irradiation on mechanical properties, IASCC susceptibility, microstructure, and grain boundary chemistry. The study was sponsored by the Cooperative IASCC Research (CIR II) Program, an international research effort managed by EPRI.

Background

The CIR Program goal is to develop a mechanistically based predictive methodology for IASCC and to identify potential countermeasures for IASCC.

Objectives

To conduct neutron irradiations of a set of materials with tailored compositions and microstructures that will be used to isolate critical metallurgical variables believed to influence IASCC.

Approach

EPRI's CIR II Program sponsored irradiation of test materials in the BOR-60 fast breeder reactor of the Research Institute for Atomic Reactors (RIAR, Dimitrovgrad, Russia). The Boris (BOR-60 Internals Study) experiments consisted of annual irradiation cycles in the BOR-60 reactor, each of which provided a fluence of ~20 dpa at a temperature close to 320°C. CIR materials irradiated in the Boris 6 experiment included four austenitic stainless steels representative of the materials for the LWR core internals (solution annealed 304L, solution annealed 316, cold worked 316, and cold worked 316 titanium stabilized) as well as two tailored materials (high-purity 304L and high-purity 304L with molybdenum added). The materials irradiated in Boris 7 experiment included LWR core internals and high-purity type 304L tailored alloys with additions of chromium, nickel, molybdenum, silicon, titanium, niobium, and hafnium. The CIR-II program used one-half of the rig from the Boris 6 experiment and one-half of the rig from the Boris 7 experiment.

Results

This report discusses the principles behind the Boris experiment as well as procedures for temperature and neutron monitoring. It also describes the austenitic specimens irradiated in the Boris 6 and 7 experiments, irradiation conditions for the Boris 6 and 7 experiments, and results of the tensile tests performed after these irradiations. The specimens (tensile, round compact tension, and 3-mm discs) received damage doses between 5 and 45 dpa at a temperature of ~320°C. The engineering tensile curves are typical of austenitic stainless steels irradiated at low temperature, with significantly high yield strength, little strain hardening, and early necking, but with reductions of area that are not affected by irradiation and remain very high.

EPRI Perspective

Studies such as this one involving irradiations in the BOR-60 fast reactor will help predict long-term material degradation and aging of irradiated LWR components with increasing operating life and neutron dose. The crack growth and transmission electron microscopy (TEM) disc specimens in this program will be tested at other laboratories to evaluate IASCC susceptibility and microstructure/microchemistry. EPRI issued an interim report (1009418) on the Boris 6 experiment of the CIR II Program in March 2004. This final report on Boris 6 and 7 irradiations supersedes the previous report.

Keywords

Irradiation-Assisted Stress Corrosion Cracking

Austenitic Stainless Steel

Neutron Flux

Fast Reactor

Tensile Tests

ABSTRACT

The international CIR II Program (Cooperative IASCC Research Program) has initiated a R&D programme based upon the irradiation of test materials in the BOR-60 fast breeder reactor of the Research Institute for Atomic Reactors (RIAR, Dimitrovgrad, Russia), at a temperature close to 320°C (Boris experiments). The present report describes the principle of the Boris experiment, and especially the conditions for temperature and neutron monitoring. It also gives the description of the specimens irradiated in the Boris 6 and 7 experiments, the irradiation conditions for the Boris 6 and 7 experiments and the results of the tensile tests performed after these irradiations.

EXECUTIVE SUMMARY

-
- Context: LWR internals located very close to the core are highly irradiated and can be affected by Irradiation-Assisted Stress Corrosion Cracking (IASCC). The Cooperative IASCC Research (CIR phase II) Program is being sponsored by different member organizations to develop a mechanistic understanding of the key parameters controlling IASCC.
 - Objectives: One of the CIR II objectives is the experimental irradiation of a set of materials with tailored compositions and microstructures that will be used to isolate critical metallurgical variables believed to influence IASCC.
 - Methodology: In order to meet this objective, the CIR II Program has initiated a R&D programme based upon the irradiation of test materials in the BOR-60 fast breeder reactor of the Research Institute for Atomic Reactors (RIAR, Dimitrovgrad, Russia). The BORIS (**BOR**-60 Internals Study) experiments are the irradiations cycles in this reactor. They comprise annual irradiation cycles each providing about 20 dpa at a temperature close to 320°C. The CIR-II program uses ½ rig of the Boris 6 experiment and ½ rig of the Boris 7 experiment.
 - Results: This report describes the principle of the Boris experiment, and especially the conditions for temperature and neutron monitoring. It also gives the description of the specimens irradiated in the Boris 6 and 7 experiments, the irradiation conditions for the Boris 6 and 7 experiments and the results of the tensile tests performed after these irradiations.
 - The specimens have received damage doses between 5 and 45 dpa. The temperature of the specimens was ~320°C.

This report gives a brief description of the CIR materials involved in the Boris 6 experiment: five materials representative of the materials for the core internals (2 solution annealed 304L, solution annealed 316, cold worked 316, and cold worked 316 Titanium stabilized) and different tailored materials (high purity 304L and high purity 304L with Molybdenum, Silicon, Nickel, Titanium or Hafnium added).

The results of the tensile tests performed after irradiation on these materials are also given. The engineering tensile curves are typical of austenitic stainless steels irradiated at low temperature: very high yield strength, very little strain hardening and early necking, but with reductions of area which are not affected by irradiation and remain very high. Except for solution annealed 316, the results are in good agreement with previous results.

- Perspective: The irradiations in the Bor-60 reactor are finished.

CONTENTS

1 OBJECTIVE.....	1-1
2 GENERAL DESCRIPTION OF THE BOR-60 REACTOR.....	2-1
3 DESCRIPTION OF THE EXPERIMENTAL RIG FOR THE BORIS 6 AND 7 EXPERIMENTS	3-1
4 SPECTRUM - FLUX - DAMAGE	4-1
4.1 Description of the Rig Location in the Core of Bor-60 Reactor	4-1
4.2 Dosimetry	4-1
4.3 Fast Neutron Spectrum	4-2
4.4 Fast Neutron Flux.....	4-2
4.5 Calculation of Irradiation Damage (dpa-NRT)	4-2
4.6 Gas Production Rate	4-2
5 THERMAL CONDITIONS.....	5-1
5.1 Sodium Coolant Flow Inside the Test Rig	5-1
5.2 Gamma Heating	5-2
5.3 Calculation of the Temperature	5-2
5.4 Thermal Monitors	5-3
5.5 Monitoring of the Irradiation.....	5-3
6 BORIS 6 AND 7 EXPERIMENTS	6-1
6.1 Description of the Materials and Specimens for the Boris 6 and 7 Experiments.....	6-1
6.2 Irradiation Conditions for the Boris 6 and 7 Experiments.....	6-9
6.2.1 Neutron Monitoring	6-9
6.2.2 Temperature Monitoring	6-9
6.3 Specimens Available for Post Irradiation Tests.....	6-15
7 TENSILE TESTS RESULTS	7-19

7.1 Method	7-19
7.2 Results	7-20
7.2.1 Commercial Grades.....	7-20
the dose constant characterises the “rate of degradation” and is close to 3 dpa.	7-21
7.2.2 Tailored Alloys	7-21
8 CONCLUSIONS	8-1
8.1 References	8-1
A SPECIMENS DESIGN	A-1
B TEM CAPSULES CONTENT	B-1
C STRESS-STRAIN CURVES	C-1

LIST OF FIGURES

Figure 2-1 Bor-60 Vessel Cross Section: 1, 6 - Inlet and Outlet Connections; 2- Inlet Chamber of the Pressure Collector; 4 - Thermal and Neutron Shielding; 5 - Protective Vessel; 9 - Control Rod; 11, 12 - Large and Small Rotating Plugs; 13 - Refuelling Channel; 14 - Core Assembly and Radial Blanket Assembly.....	2-2
Figure 2-2 Bor-60 Core: 1: Fuel Assembly; 2 - Radial Blanket Assembly; 3 - D-23 Cell (with Thermocouple)	2-3
Figure 2-3 Bor-60 Fuel Assembly: 1 - Head; 3 - Fuel Element End Plug; 4 - Upper Blanket; 5 - Fuel Column; 6 - Hexagonal Wrapper Tube; 7 - Gas Plenum; 8 - Tail	2-4
Figure 3-1 Schematic Description of the Rig	3-3
Figure 3-2 Schematic Description of the Boris Irradiation Rig: - Foot of the Rig - Capsule with the Seven Specimen Baskets, - Top of the Rig with the Thermocouples	3-4
Figure 3-3 Schematic Description of a Basket Settled in its Hexagonal Tube	3-5
Figure 4-1 Fast Neutron Spectrum of the Bor-60 Fast Breeder Reactor. Calculation by RIAR for the D-23 Cell, Central Plane (Z = 0 mm)	4-3
Figure 4-2 Fast Neutron Spectrum of Bor-60 for D-23 Cell (Stage 2), Characterized by a Set of Dosimeters with the Following Energy Thresholds: $\text{Nb}^{93}(\text{n}, 2\text{n}) \text{Nb}^{93\text{m}}$: 1.0 MeV $\text{Ni}^{58}(\text{n}, \text{p}) \text{Co}^{58}$: 2.5 MeV $\text{Fe}^{54}(\text{n}, \text{p}) \text{Mn}^{54}$: 3.0 MeV $\text{Ti}^{46}(\text{n}, \text{p}) \text{Sc}^{46}$: 4.6 MeV $\text{Cu}^{63}(\text{n}, \alpha) \text{Co}^{60}$: 7.0 MeV	4-3
Figure 4-3 Fast Neutron ($E > 0.1$ MeV) Flux in the D-23 Cell at 55 MWt. The Flux has been Assessed Assuming: - The Fluence Measured by Dosimetry; - The Duration of the Irradiation (at 55 MWt) Calculated using the Recorded Reactor Energy Production	4-4
Figure 4-4 Damage Rate in the D-23 cell at 55 MWt for Type 316 Stainless Steel. The Damage Rate has been Assessed Assuming: - The Damage Calculated by RIAR by Dosimetry; - The Duration of the Irradiation (at 55 MWt) Calculated from the Recorded Reactor Energy Production	4-4
Figure 6-1 Thermal Power and Sodium Temperature Measured during the Boris 6 Experiment	6-14
Figure 6-2 Thermal Power and Sodium Temperature Measured during the Boris 7 Experiment	6-14
Figure 7-1 Yield Stress (at 330°C) as a Function of Damage Dose	7-22
Figure 7-2 Ultimate Tensile Strength (at 330°C) as a Function of Damage Dose	7-23
Figure 7-3 Uniform Elongation (at 330°C) as a Function of Damage Dose	7-23
Figure 7-4 Total Elongation (at 330°C) as a Function of Damage Dose.....	7-24
Figure 7-5 Yield Stress (at 330°C) at 10 dpa for the Different Tailored Materials.....	7-24
Figure 7-6 Uniform Elongation (at 330°C) at 10 dpa for the Different Tailored Materials	7-25

Figure 7-7 Total Elongation (at 330°C) at 10 dpa for the Different Tailored Materials	7-25
Figure 7-8 Comparison of the Yield Strength Data for these Neutron Irradiations to the Proton Irradiation Hardness Data for the Same Alloys Using Conversion Formula to go from YS to Hardness Developed in the CIR Program	7-26
Figure A-1 Cylindrical Tensile Test Specimens Irradiated in the Different Reactor	A-1
Figure A-2 Drawing of RCT Specimens Irradiated in Boris for the CIR-II Program	A-1
Figure A-3 CT Sample Design	A-2
Figure A-4 ANL Tensile Specimen Design	A-3
Figure C-1 Tensile Curves. Commercial Grades	C-2
Figure C-2 Tensile Curves. Tailored Alloys	C-3
Figure C-3 Tensile Curves. Tailored Alloys	C-4

LIST OF TABLES

Table 3-1 Relative Elevation of the Fuel, the Specimen Baskets (Shelves) and Thermal Gas Shield. The Position of Each Individual Basket is given in Table 4-1	3-2
Table 5-1 Results of Hydraulic Characterization of the Rig	5-1
Table 6-1 CIR Materials Irradiated in the Boris 6 and 7 Experiment: Chemical Composition (Weight %)	6-2
Table 6-2 ANL-NRC Materials (Flat Tensile Specimens) Irradiated in the Boris 6 Experiment: Chemical Composition (Weight %)	6-3
Table 6-3 List and Location of the CIR and ANL Specimens Irradiated in the Boris 6R1-1 Experiment	6-4
Table 6-4 List and Location of the Specimens in Baskets 6 and 7 Irradiated in the Boris 6R1-2 Experiment. The Specimens in Baskets 1 to 5 are the same as those in Boris 6R1-1	6-5
Table 6-5 List and Location of the Specimens Irradiated in the Boris 6R1-3 Experiment The Specimens in Baskets 1 to 5 are the same as those in Boris 6R1-1 and 6R1-2.....	6-6
Table 6-6 List and Location of the CIR and ANL Specimens Irradiated in the Boris 7-1 Experiment	6-7
Table 6-7 List and Location of the Specimens in Baskets 5, 6 and 7 Irradiated in the Boris 7-2 Experiment. The Specimens in Baskets 1 to 4 are the same as those in Boris 7-1 (in Basket 4 only Specimen BS03 was Removed et Replaced with Specimen SW02)	6-8
Table 6-8 List and Location of the Specimens Irradiated in the Boris 7-3 Experiment. The Specimens in Baskets 1 to 4 and 6 and 7 are the same as those in Boris 7-2	6-8
Table 6-9 Irradiation Conditions for the Boris 6 Experiment	6-11
Table 6-10 Irradiation Conditions for the Boris 7 Experiment	6-12
Table 6-11 Boris 6: Damage (dpa-NRT*) for each Specimen Basket.....	6-13
Table 6-12 Boris 7: Damage (dpa-NRT*) for each Specimen Basket.....	6-13
Table 6-13 List of RCT Specimens Available for Crack Growth Tests After Boris 6.....	6-15
Table 6-14 List of RCT Specimens Available for Crack Growth Tests After Boris 7.....	6-16
Table 6-15 List of Tensile* and SSRT Specimens Available After Boris 6.....	6-16
Table 6-16 List of Tensile* and SSRT Specimens Available After Boris 7.....	6-17
Table 6-17 List of TEM Capsules Available After Boris 6	6-18
Table 6-18 List of TEM Capsules Available After Boris 7	6-18
Table 7-1 Results of the Tensile Tests (1)	7-27
Table 7-2 Results of the Tensile Tests (2)	7-28

Table 7-3 Results of the Tensile Tests (3)	7-29
Table 7-4 Comparison of Tensile Tests Results After 10dpa Irradiation on Same Material Previously Solution Annealed in the Frame of CIR Program and in an other Frame (EDF-CEA)	7-29
Table B-1 CIR 5A Capsule.....	B-1
Table B-2 CIR 5B Capsule.....	B-3
Table B-3 CIR 10A Capsule.....	B-5
Table B-4 CIR 10B Capsule.....	B-7
Table B-5 CIR 20A Capsule.....	B-9
Table B-6 CIR 20B Capsule.....	B-11
Table B-7 CIR IIA Capsule.....	B-13
Table B-8 CIR IIB Capsule.....	B-15

1

OBJECTIVE

LWR internals located very close to the core are highly irradiated and can be affected by Irradiation-Assisted Stress Corrosion Cracking (IASCC). The Cooperative IASCC Research (CIR phase II) Program is being sponsored by different member organizations to develop a mechanistic understanding of the key parameters controlling IASCC. One of the CIR II objectives is the experimental irradiation of a set of materials with tailored compositions and microstructures that will be used to isolate critical metallurgical variables believed to influence IASCC.

In order to meet this objective, the CIR II Program has initiated a R&D programme based upon the irradiation of test materials in the BOR-60 fast breeder reactor of the Research Institute for Atomic Reactors (RIAR, Dimitrovgrad, Russia), at a temperature close to 320°C. The BORIS (**BOR-60 Internals Study**) experiments are the irradiation cycles in this reactor. They comprise annual irradiation cycles each providing neutron doses of about 20 dpa. The CIR-II program uses ½ rig of the Boris 6 experiment and ½ rig of the Boris 7 experiment.

The objective of this report is to describe the principle of the Boris experiment, especially the irradiation conditions and methods for temperature and neutron monitoring. The specimens irradiated in the Boris 6 and 7 experiments, the irradiation conditions for the Boris 6 and 7 experiments and the results of the tensile tests performed after these irradiations are also described.

This work was supported by the CIR-II program and managed by EPRI, Palo Alto, CA, under contract No. EPRI EP-P5487/C2724.

2

GENERAL DESCRIPTION OF THE BOR-60 REACTOR

Bor-60 is an experimental fast breeder reactor located near Dimitrovgrad, Russia, and has been operated by RIAR since 1969 [1]. The reactor is being used for various R&D activities (fuel elements, structural materials, etc) as well as steam and electric power production.

A general cut-away view of the vessel and core of the reactor is given in Figure 2-1. The reactor has 265 cells where the hexagonal fuel assemblies of the core and the radial blanket assemblies are situated (Figures 2-2 and 2-3). The number of fuel assemblies can vary from 85 to 114, depending on the burn-up, core arrangement and properties of the fuel used. The fuel column length is 450 mm. The reactor burns both UOX and MOX fuels. Depleted UO_2 blankets are adjacent to the top and bottom of the fuel column. The nominal thermal power of the reactor is 60 MWt. Thermal power is eliminated via a two-loop primary sodium circuit and two sodium-sodium 30 MWt heat exchangers. The reactor is equipped with a 12 MWe turbo-generator. The main characteristics of the reactor coolant are:

- temperature of the inlet primary sodium: ~300-330°C;
- temperature of the outlet primary sodium: ~ 530°C;
- primary sodium flow rate: ~ 700-1200 m³/h.

General Description of the Bor-60 Reactor

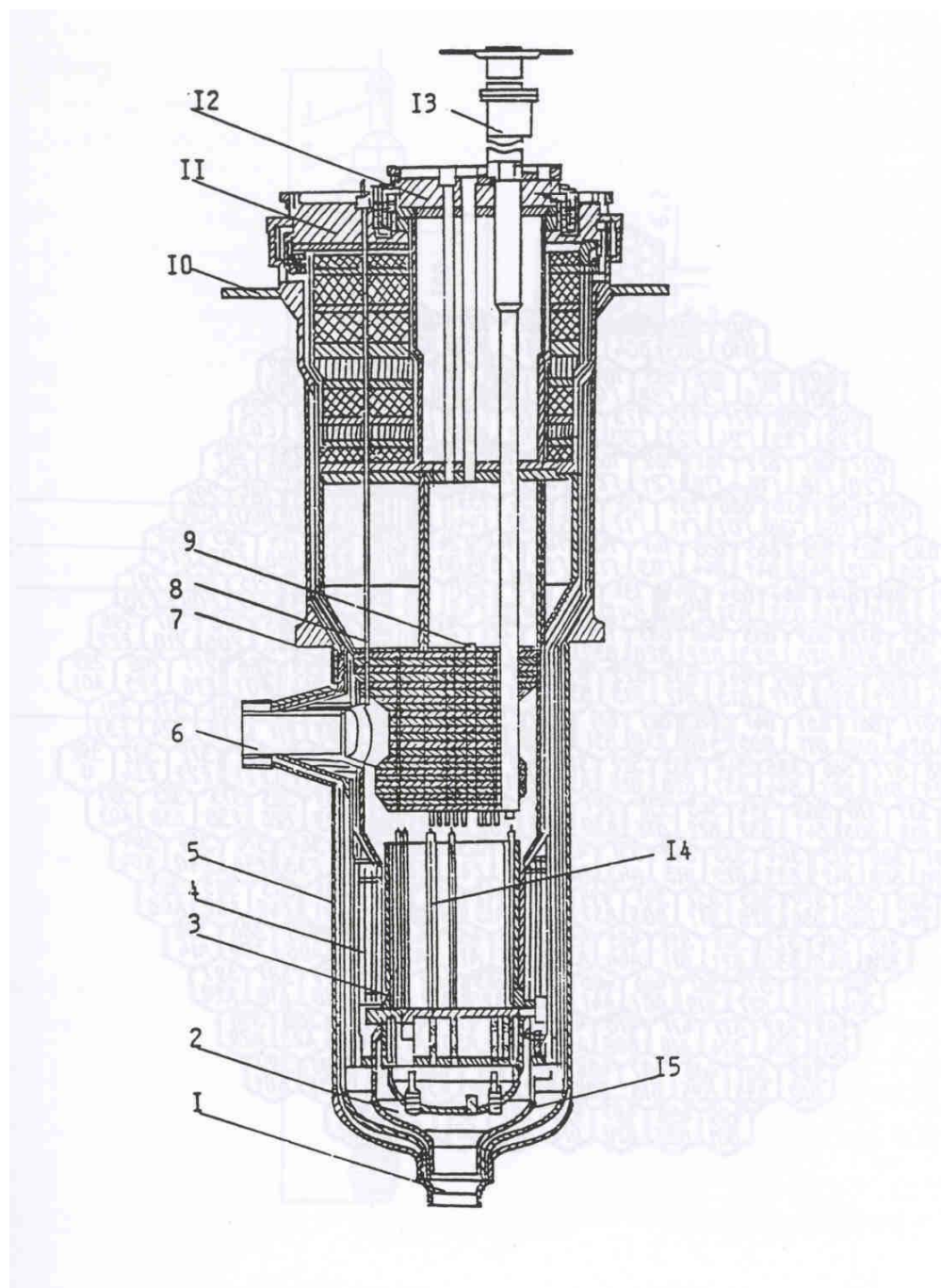


Figure 2-1
Bor-60 Vessel Cross Section:
 1, 6 - Inlet and Outlet Connections;
 2- Inlet Chamber of the Pressure Collector;
 4 - Thermal and Neutron Shielding;
 5 - Protective Vessel;
 9 - Control Rod;
 11, 12 - Large and Small Rotating Plugs;
 13 - Refuelling Channel;
 14 - Core Assembly and Radial Blanket Assembly

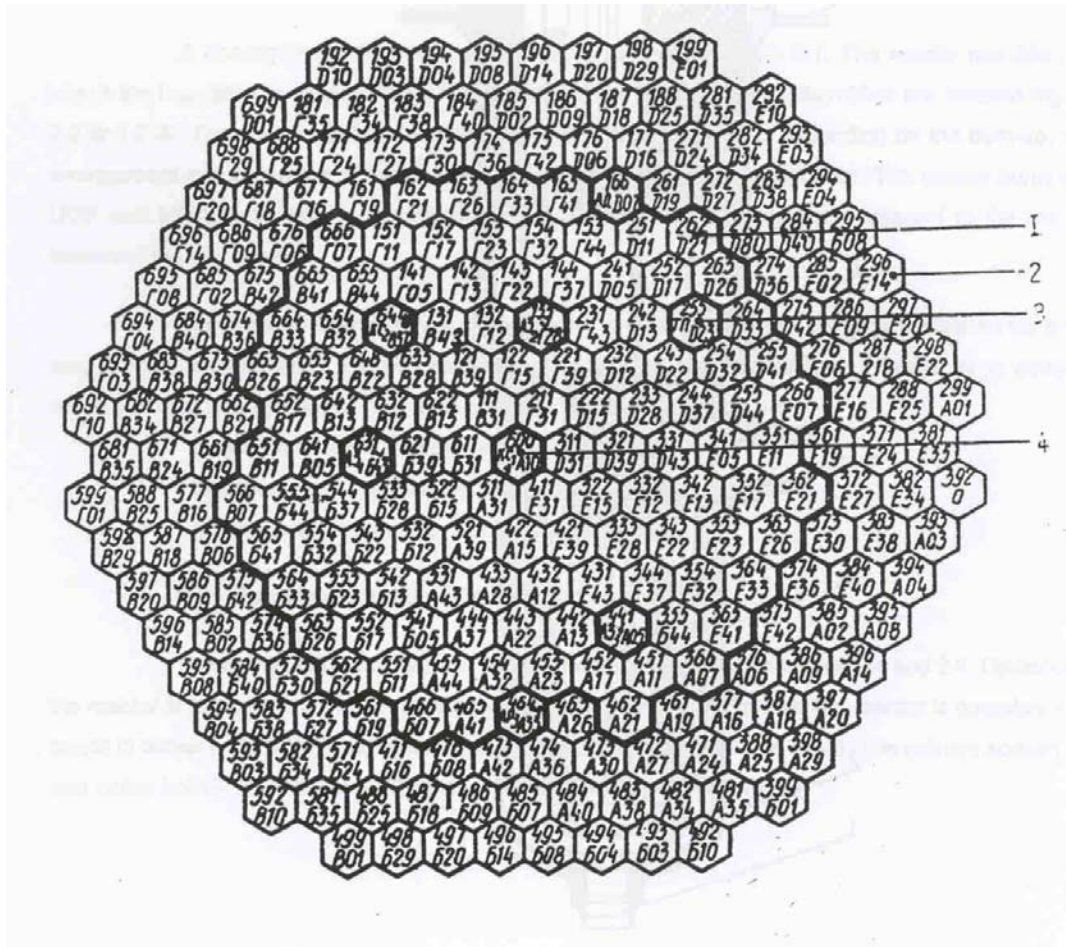


Figure 2-2
Bor-60 Core:
 1: Fuel Assembly;
 2 - Radial Blanket Assembly;
 3 - D-23 Cell (with Thermocouple)

General Description of the Bor-60 Reactor

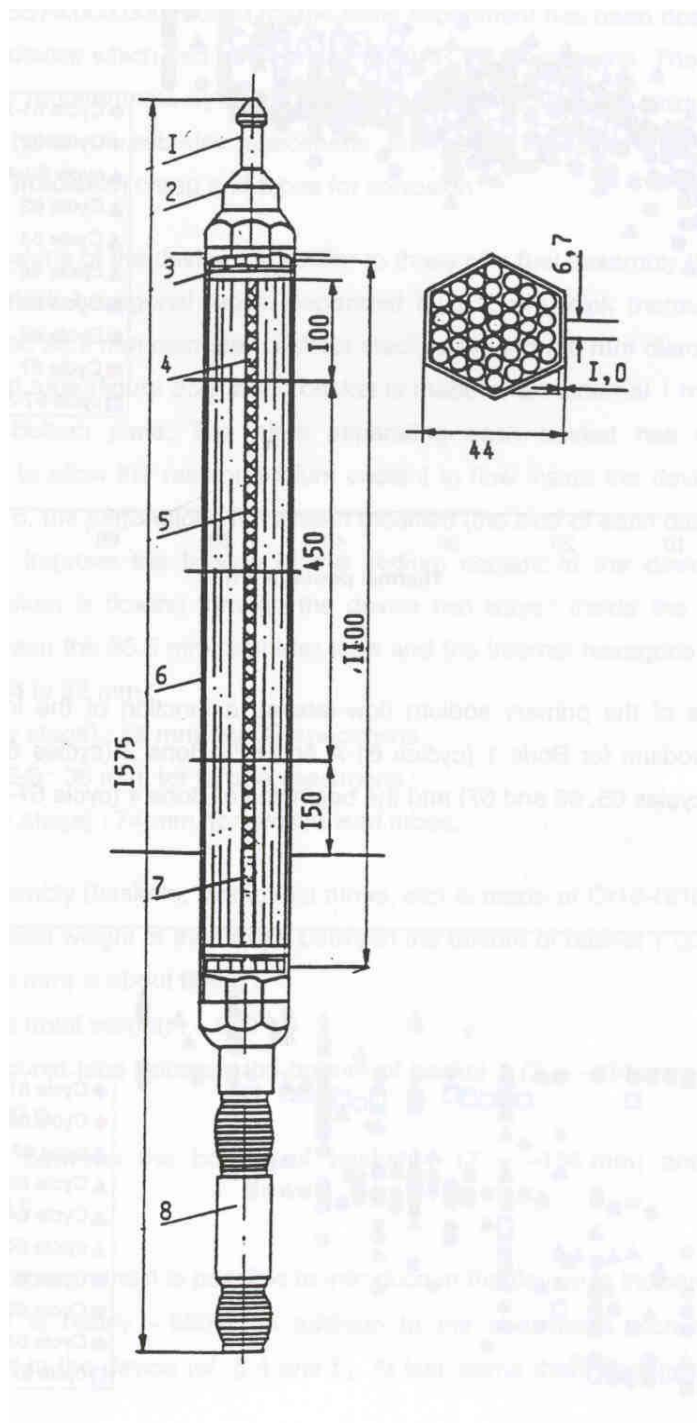


Figure 2-3
Bor-60 Fuel Assembly:
 1 - Head;
 3 - Fuel Element End Plug;
 4 - Upper Blanket;
 5 - Fuel Column;
 6 - Hexagonal Wrapper Tube;
 7 - Gas Plenum;
 8 - Tail

3

DESCRIPTION OF THE EXPERIMENTAL RIG FOR THE BORIS 6 AND 7 EXPERIMENTS

The rig used for the Boris experiment was designed by RIAR. It is very similar to previous rigs which had been in use at RIAR for many years. The former rig design was modified to meet the requirements specified by EDF-CEA for the Boris experiment (in particular the size of the specimens to be irradiated and the desired irradiation temperature).

The external dimensions of the rig are similar to those of a fuel assembly (Figure 3-1). The rig is made of two 1 mm thick hexagonal tubes, separated by a 2 mm thick thermal gas shield (argon). A capsule is made from seven 35.5 mm diameter baskets stacked around a 6 mm diameter tube that is inserted into an internal hexagonal tube (Figure 3-2). Each basket is made from an external 1 mm thick tube attached to a 1.5 mm thick bottom plate. The plate separating each basket has sixteen 4 mm diameter perforations in order to allow the reactor sodium coolant to flow inside the rig and over the specimens. The side of each basket is perforated in order to improve the sodium coolant flow in the rig and to homogenize its temperature. The sodium flows through the device in two ways: inside the 35.5 mm tube, over the specimens, and also between the 35.5 mm diameter tube and the internal hexagonal tube. The height of the baskets varies from 36 to 62 mm:

- shelf 7 (upper stage): 55 mm;
- shelves 2-3-4-5-6: 36 mm;
- shelf 1 (lower stage): 74 mm.

The whole assembly (baskets, hexagonal tubes, etc) is made of Cr18-Ni10-Ti1 austenitic stainless steel.

Dosimeters are placed in the central tube at the level of each basket (or shelf). In addition to the specimens. Thermal monitors and dosimeters are also placed in the rig. Finally, some thermocouples are placed in the upper part of the rig.

After each irradiation experiment, the rig and specimens are cleaned (by immersion in a mixture of 50 % water and 50 % alcohol) and then, the device is dismantled. Some of the irradiated specimens are usually replaced by fresh specimens together with new dosimeters and new thermal monitors.

Description of the Experimental Rig for the Boris 6 and 7 Experiments

Table 3-1
Relative Elevation of the Fuel, the Specimen Baskets (Shelves) and Thermal Gas Shield.
The Position of Each Individual Basket is given in Table 4-1

Axial Position (mm)	Element
+ 261	top of thermal gas shield
+ 236	upper thermocouple for measurement of outlet sodium coolant temperature
+ 216	lower thermocouple for measurement of outlet sodium coolant temperature
+ 225	top of zone fissile of fuel assemblies
+ 166	top of basket 7
0	bottom of basket 4 central plane of the core top of basket 3
- 134	bottom of basket 1
- 225	bottom of zone fissile of fuel assemblies
- 615	bottom of thermal gas shield (argon). The lower limit of the thermal shield is associated with the pressure balance between sodium, and argon.

Description of the Experimental Rig for the Boris 6 and 7 Experiments

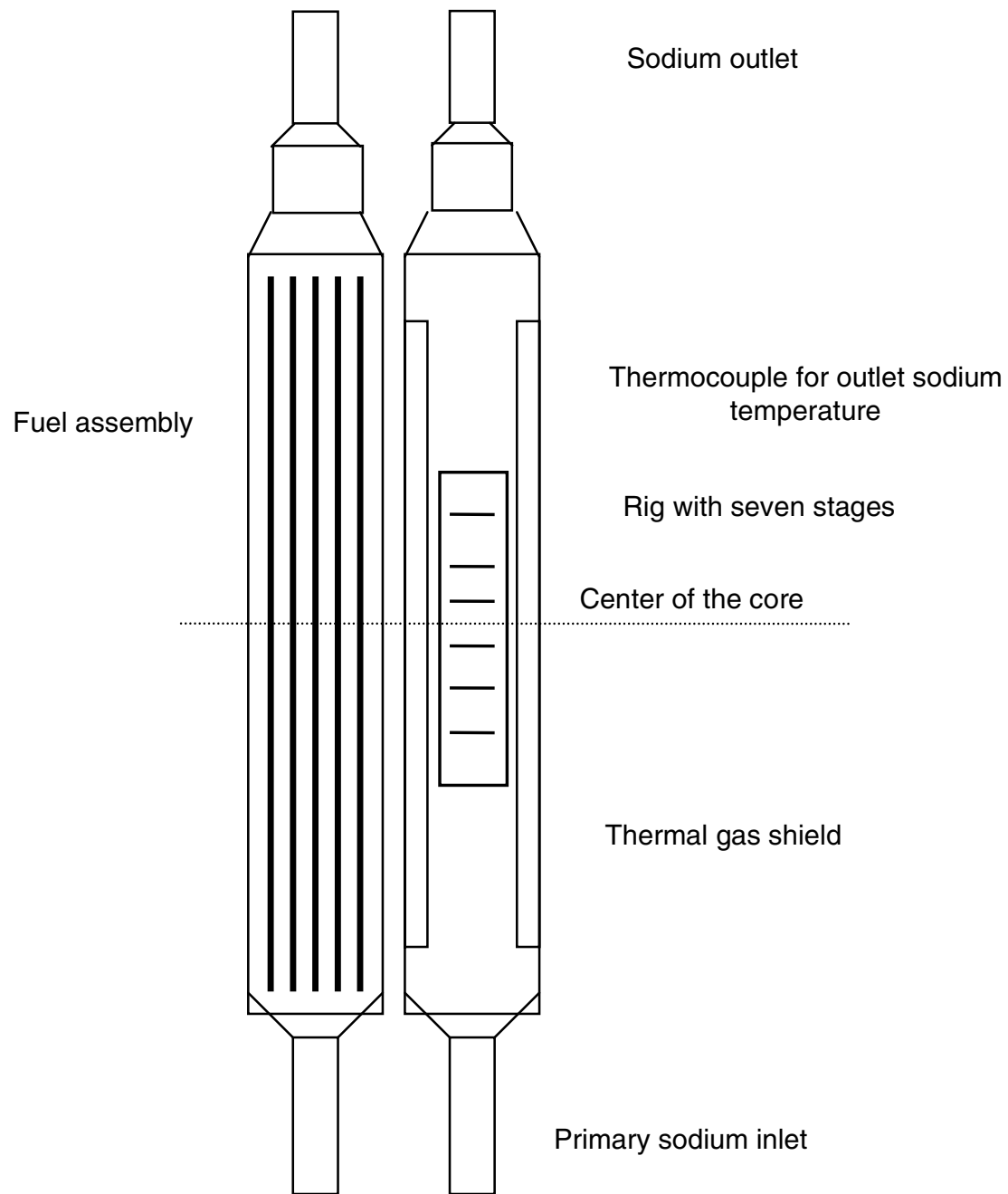


Figure 3-1
Schematic Description of the Rig

Description of the Experimental Rig for the Boris 6 and 7 Experiments

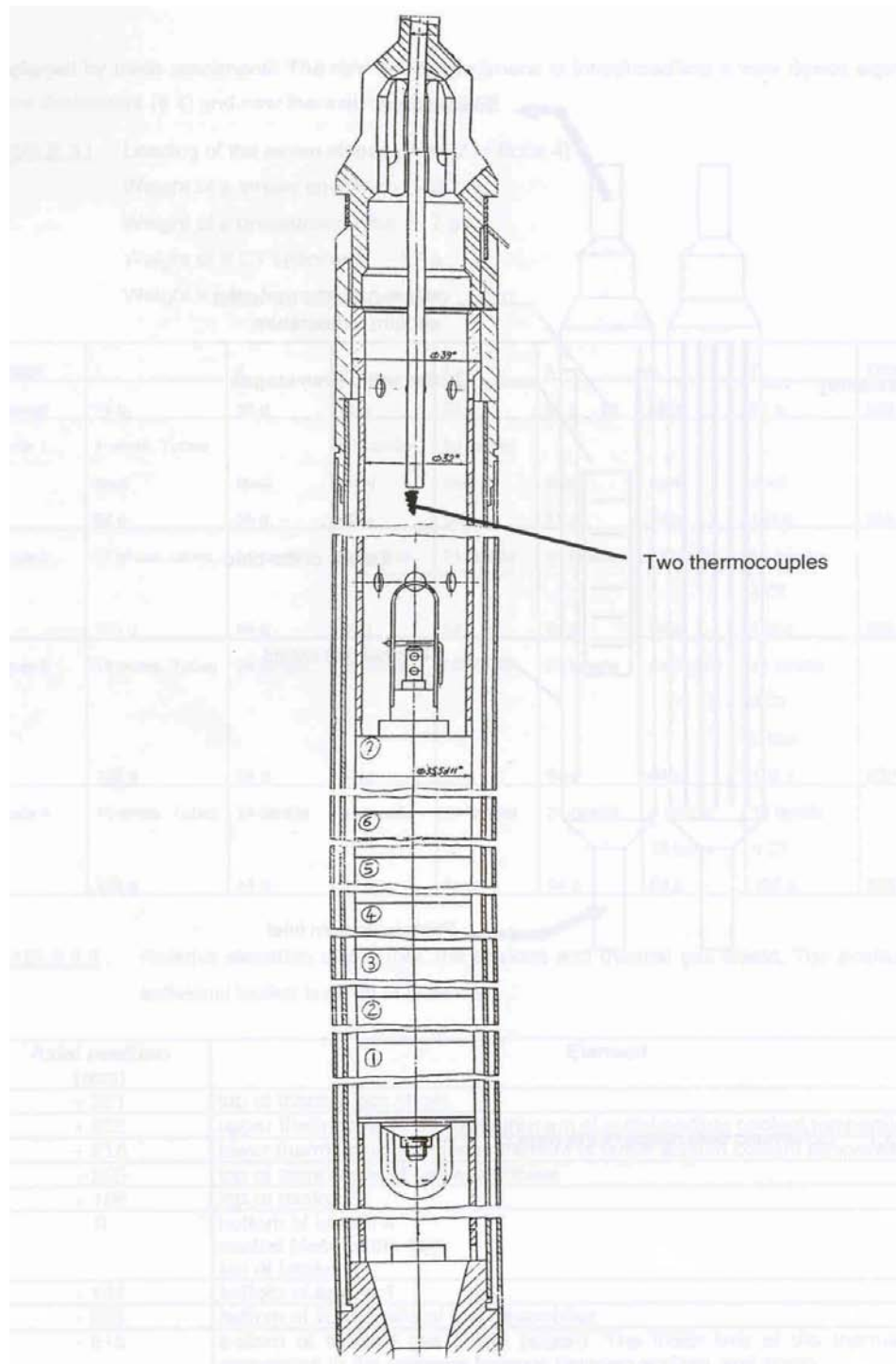


Figure 3-2
Schematic Description of the Boris Irradiation Rig:
 - Foot of the Rig
 - Capsule with the Seven Specimen Baskets,
 - Top of the Rig with the Thermocouples

Description of the Experimental Rig for the Boris 6 and 7 Experiments

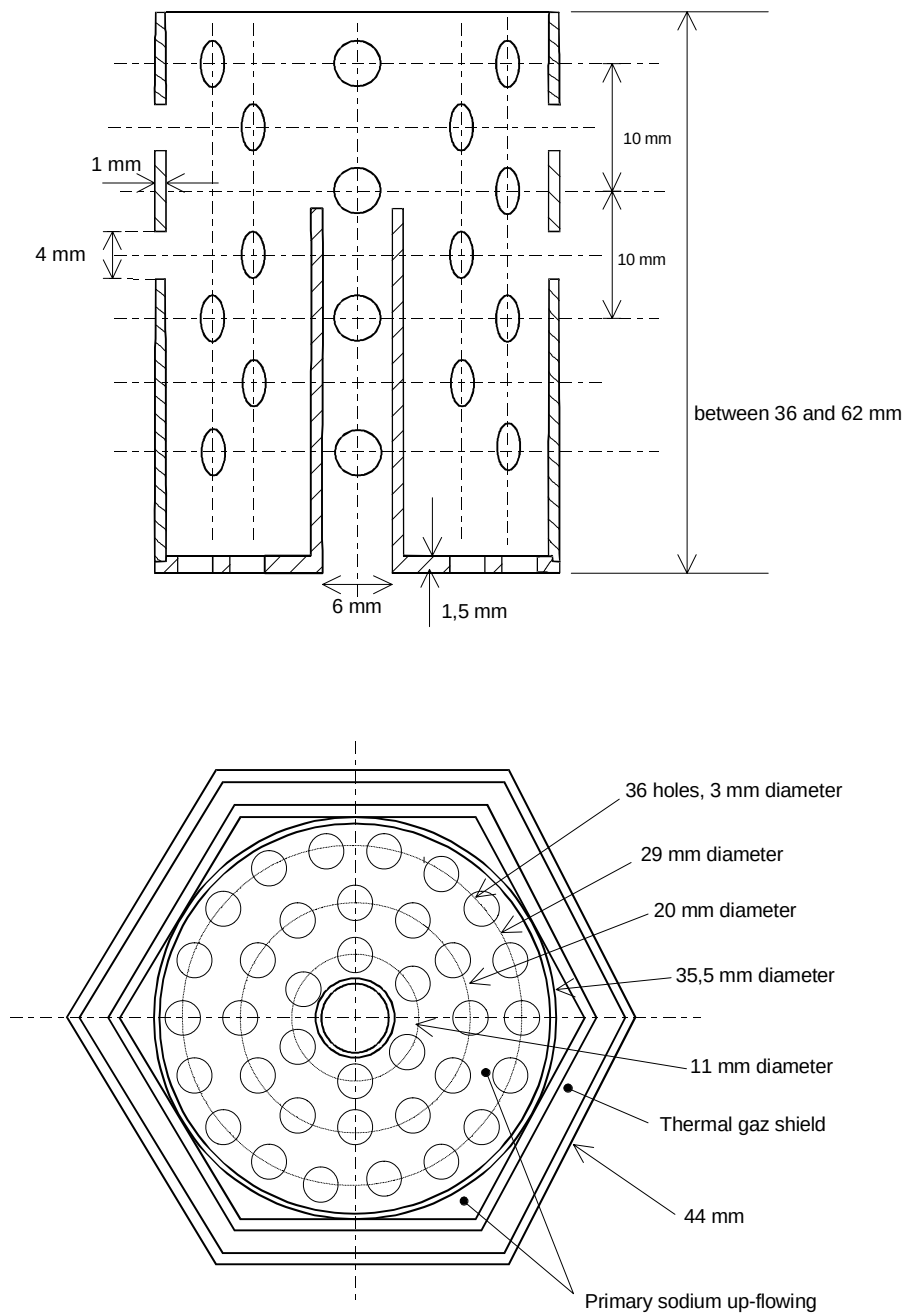


Figure 3-3
Schematic Description of a Basket Settled in its Hexagonal Tube

4

SPECTRUM - FLUX - DAMAGE

4.1 Description of the Rig Location in the Core of Bor-60 Reactor

From preliminary experiments to verify the neutron flux and irradiation temperature specifications, the rig was located in the D-23 cell of the fifth row of the core, at ~ 196 mm from the central axis of the core (Figure 2-2). D-23 is one cell of the core which permits on-line measurement of the temperature of sodium at the outlet of the capsule. The six cells surrounding the experimental cells have always been occupied by fuel assemblies. The number of fuel assemblies is kept constant over the period of the experiment. The radial blanket is primarily made of steel.

4.2 Dosimetry

In addition to the calculations performed by RIAR, neutron fluxes and spectra are characterized by dosimetry. The use of a series of nuclear reactions with various energy thresholds enables a fine calibration of the neutron spectrum.

Before starting Boris experiments, RIAR performed a full characterisation of the neutron flux in the D-23 cell, for each shelf of the rig using a set of eight dosimeters: $\text{Rh}^{103} (n, 2n) \text{Rh}^{103m}$, $\text{In}^{115} (n, 2n) \text{In}^{115m}$, $\text{Ti}^{47} (n, p) \text{Sc}^{47}$, $\text{Ni}^{58} (n, p) \text{Co}^{58}$, $\text{Fe}^{54} (n, p) \text{Mn}^{54}$, $\text{Ti}^{46} (n, p) \text{Sc}^{46}$, $\text{Ti}^{48} (n, p) \text{Sc}^{48}$, $\text{Nb}^{93} (n, 2n) \text{Nb}^{93m}$. Based on those measurements, the calculated neutron spectrum was corrected.

For each individual experiment, the fluence was estimated by five dosimeters produced and analysed by RIAR for each shelf: $\text{Ni}^{58} (n, p) \text{Co}^{58}$, $\text{Fe}^{54} (n, p) \text{Mn}^{54}$, $\text{Ti}^{46} (n, p) \text{Sc}^{46}$, $\text{Nb}^{93} (n, 2n) \text{Nb}^{93m}$ and $\text{Cu}^{63} (n, \alpha) \text{Co}^{60}$. Monitors were made of 1 mm diameter discs wrapped in 3 mm diameter quartz capsules. These capsules were then placed in stainless steel containers. Dosimeters were introduced in the central channel of the rig and a few dosimeters were also placed in the baskets among the specimens.

The accuracy of the measurement of fluence via dosimetry was estimated to be better than 7 %. A comparison of the quality of dosimetry measurements between RIAR and several other European laboratories has been carried out [2]: Petten, VTT, SCK-ECN and SZK laboratories were involved in the comparison. It included three dosimeters of the type $\text{Ni}^{58} (n, p) \text{Co}^{58}$, $\text{Fe}^{54} (n, p) \text{Mn}^{54}$ and $\text{Ti}^{46} (n, p) \text{Sc}^{46}$, similar to those used in the Boris experiments which were irradiated in the Korpus reactor at RIAR. The difference in the results obtained by RIAR and those obtained by other laboratories was less than 3 %, for the three types of dosimeters.

4.3 Fast Neutron Spectrum

For each individual experiment, RIAR performed a calculation of the neutron spectrum for the D-23 cell at the central plane of the core ($Z = 0$ mm). The results of the dosimetry were taken into account as a correction factor for the calculation of the neutron spectrum. The results are given in Figure 4-1.

4.4 Fast Neutron Flux

The neutron flux was calculated by RIAR (as shown in Figure 4-1). In addition, the fast neutron flux was determined based on (i) the fluence measured at each shelf by dosimetry and (ii) the duration of the irradiation calculated from the recorded reactor energy production (Figure 4-3). At the elevation of the central plane of the core ($Z = 0$ mm) and for a nominal reactor power of 55 MWt, the measured neutron flux was close to:

$$\sim 2.2 \times 10^{15} \text{ n cm}^{-2} \text{ s}^{-1} (E > 0 \text{ MeV})$$

$$\sim 0.83 \times 2.2 = 1.8 \times 10^{15} \text{ n cm}^{-2} \text{ s}^{-1} (E > 0.1 \text{ MeV});$$

The axial distribution of the fast neutron flux was relatively flat from shelf 1 to shelf 5: differences were less than 15 %. The flux at shelf 7 was about 30 % lower than the flux at shelves 3-4. An experimental characterization of the radial distribution of the neutron flux in the rig was also performed for the Boris 4 and 5 experiments and showed less than 8% difference between the central channel and the outer parts of the baskets.

4.5 Calculation of Irradiation Damage (dpa-NRT)

The calculation of irradiation damage (dpa-NRT) was performed by RIAR using the SPECTER code taking into account the neutron spectrum calculated by RIAR and the measurement of fluence by dosimetry at each shelf. The VNIIFTRI library of neutron cross-section was used. According to these calculations, $10^{22} \text{ n cm}^{-2}$ ($E > 0.1 \text{ MeV}$) is equivalent to ~ 5.2 dpa for Types 304 and 316 stainless steels. The damage rate at full power (55 MWt) is given in Figure 4-4 for Type 316 stainless steel. Assuming that the fast neutron flux was close to $\sim 1.8 \times 10^{15} \text{ n cm}^{-2} \text{ s}^{-1}$ ($E > 0.1 \text{ MeV}$) at full power (55 MWt), the damage rate at the central plane of the rig ($Z = 0$ mm) was close to $\sim 1.8 \times 5.2 = 9.4 \times 10^{-7} \text{ dpa s}^{-1}$. The axial distribution of the damage rate was similar to the axial distribution of the fast neutron flux (cf. § 4.4).

4.6 Gas Production Rate

RIAR has calculated the hydrogen production rate for Type 304/316 stainless steels in the D-23 cell of the Bor-60 reactor using the TRANS-MU code and spectrometric neutron-activation measurements. Up to 80 dpa, the hydrogen production rate is proportional to dose at about 7-7.5 appm dpa^{-1} . The main reactions involved in hydrogen production are $\text{Ni}^{58} (n, p) \text{Co}^{58}$, $\text{Ni}^{58} (n, p) \text{Co}^{58m}$ and $\text{Fe}^{54} (n, p) \text{Mn}^{54}$. However, it is not known whether the hydrogen diffuses out of

the steel or is trapped in sinks (dislocations, bubbles, etc...). The helium production rate is expected to be much lower than hydrogen production rate.

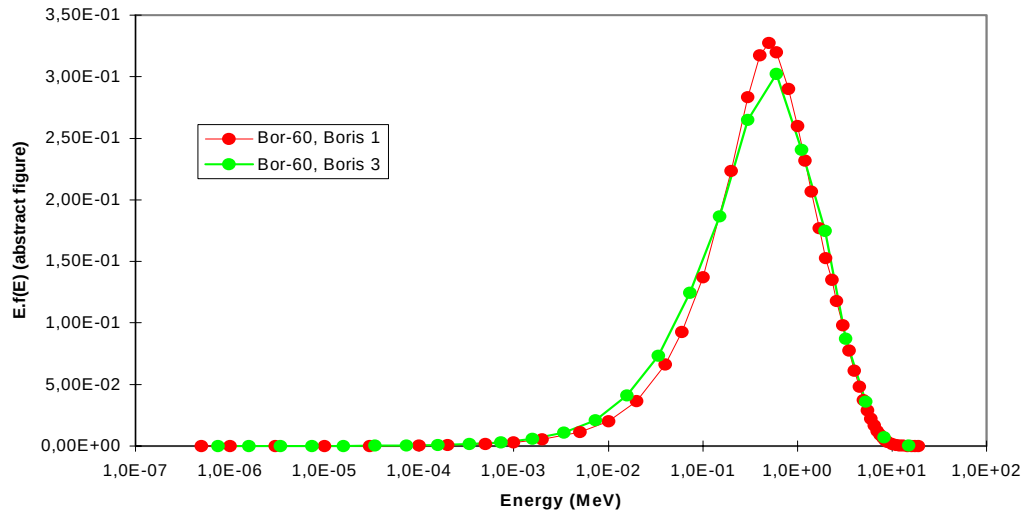


Figure 4-1
Fast Neutron Spectrum of the Bor-60 Fast Breeder Reactor. Calculation by RIAR for the D-23 Cell, Central Plane ($Z = 0$ mm)

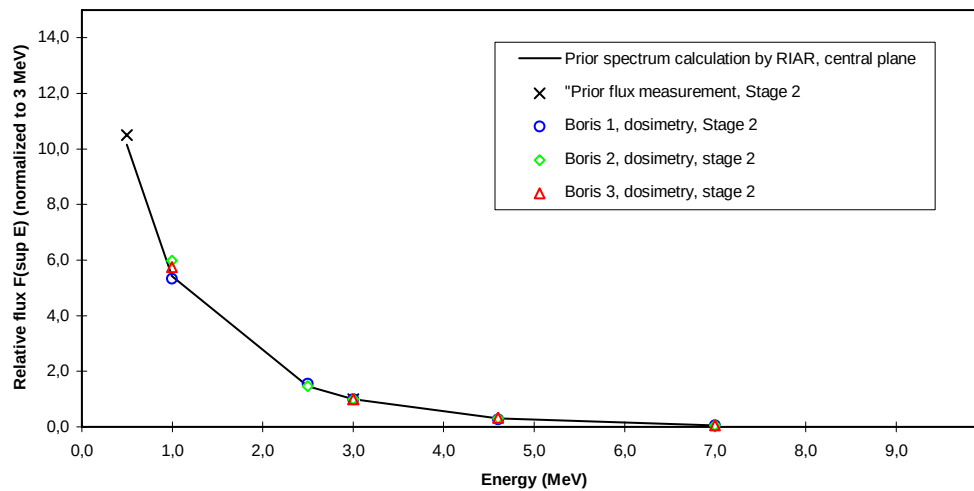


Figure 4-2
Fast Neutron Spectrum of Bor-60 for D-23 Cell (Stage 2), Characterized by a Set of Dosimeters with the Following Energy Thresholds:

$\text{Nb}^{93} (n, 2n) \text{Nb}^{93m}$: 1.0 MeV

$\text{Ni}^{58} (n, p) \text{Co}^{58}$: 2.5 MeV

$\text{Fe}^{54} (n, p) \text{Mn}^{54}$: 3.0 MeV

$\text{Ti}^{46} (n, p) \text{Sc}^{46}$: 4.6 MeV

$\text{Cu}^{63} (n, \alpha) \text{Co}^{60}$: 7.0 MeV

Spectrum - Flux - Damage

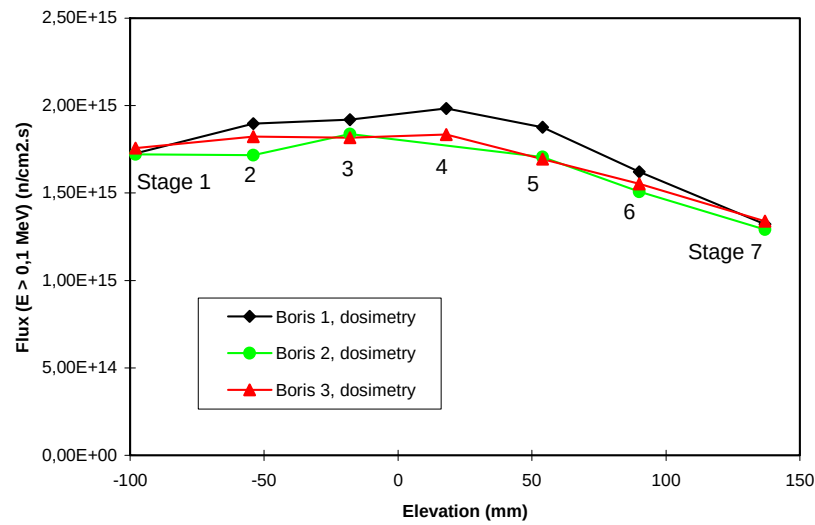


Figure 4-3

Fast Neutron ($E > 0.1$ MeV) Flux in the D-23 Cell at 55 MWt.

The Flux has been Assessed Assuming:

- The Fluence Measured by Dosimetry;
- The Duration of the Irradiation (at 55 MWt) Calculated using the Recorded Reactor Energy Production

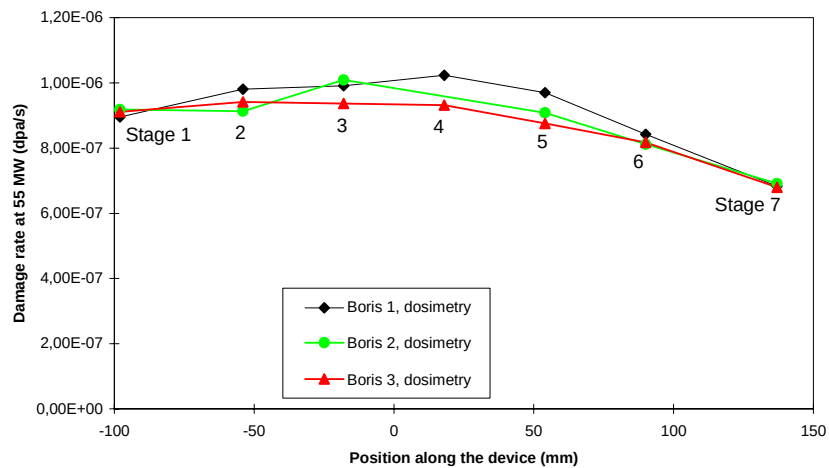


Figure 4-4

Damage Rate in the D-23 cell at 55 MWt for Type 316 Stainless Steel. The Damage Rate has been Assessed Assuming:

- The Damage Calculated by RIAR by Dosimetry;
- The Duration of the Irradiation (at 55 MWt) Calculated from the Recorded Reactor Energy Production

5

THERMAL CONDITIONS

The estimation of specimen temperatures during the irradiation is based upon (i) prior calculation by RIAR of the heating of the sodium coolant flowing inside the rig, (ii) on-line monitoring of the sodium temperature at the inlet and outlet, and (iii) analysis of some thermal fuse monitors for each irradiation cycle.

5.1 Sodium Coolant Flow Inside the Test Rig

For each experiment, a new test rig was prepared. Before each experiment, the hydraulic characteristics of the rig were measured in a water loop. For this characterization, some dummy specimens are introduced in the rig to represent the test specimens. The hydraulic behaviour was described by the following equation: $P = K_{\text{water}} \times G^2$, where P is the pressure, G the water flow rate in the rig and K_{water} a hydraulic characteristic of the rig in water.

Table 5-1
Results of Hydraulic Characterization of the Rig

P(1000 m ³ /h): primary sodium differential pressure for a primary sodium flow rate at 1000 m ³ /h (measurement by RIAR)	3.42 kg/cm ²
K_{sodium} (extrapolated by RIAR, from hydraulic testing in water)	0.055
G(1000 m ³ /h): sodium flow rate in the rig 1000 m ³ /h primary sodium flow rate (calculation: $G = [P / K_{\text{sodium}}]^{1/2}$)	7.9 m ³ /h

K_{sodium} was derived from K_{water} by means of the code PROLIV. After placing the test rig in the core of the reactor, the sodium flow was verified at zero thermal reactor power and at a primary sodium flow rate of 300 m³/h. The results of the hydraulic characterization of the test rig are given at Table 5-1. At 1000 m³/h primary sodium flow rate through the reactor core, the calculated sodium flow rate inside the rig is about 7.9 m³/h.

The total sodium flow rate in the test rig was divided in two parts:

- $\Phi 1$: the sodium flowing inside the cylindrical capsule
- $\Phi 2$: the sodium flowing between the capsule and the internal hexagonal tube.

In addition to the sodium circulating inside the test rig ($\Phi 1 + \Phi 2$), there was also a sodium flow between the fuel assemblies of about 0.1 l/s per assembly.

5.2 Gamma Heating

According to a prior characterization by RIAR, gamma heating is described by the function $g(R, Z) = 7.95 \times \cos(\pi/2 \cdot R/305) \times \cos(\pi/2 \cdot Z/270)$ in W/g at a reactor power of 40 MWt. R and Z describe the position of the calculated gamma heating from the core axis and the core central plane respectively. For the D-23 cell of the fifth row, R is 196 mm, and the gamma heating is therefore given by:

$$g(196 \text{ mm}, Z) = 4.21 \times \cos(\pi/2 \cdot Z/270).$$

Averaged over the height of the test rig, from $Z = -134$ to $Z = +166$ mm, the gamma heating is $\sim 4.21 \times 0.87 = 3.66$ W/g at 40 MWt (equivalent to 4.86 W/g at 53 MW). Gamma heating is proportional to the thermal power of the reactor.

Modifications of the core (transformation from plutonium to uranium oxides and modification to the burn-up) are believed to have had little impact on the level of gamma heating. In addition, the gamma heating in the D-23 cell does not depend strongly on the nature of the surrounding cells.

5.3 Calculation of the Temperature

Before starting the Boris experiments, RIAR performed a calculation of sodium heating using the code TIMAS. For these calculations, the following conditions were assumed:

- thermal power: 53 MWt;
- weight of the rig: ~ 1000 g;
- inlet sodium temperature: 320°C ;
- sodium flow rate in the rig: 7.1 m^3 per hour; this flow rate applies when the primary reactor sodium flow rate is 1000 m^3 per hour for a sodium differential pressure fixed at 2.55 kg/cm^2 ;

The thermal power due to gamma heating inside the rig is ~ 7151 W partitioned as follows:

- about 5151 W from the specimens, the baskets and internal hexagonal tube;
- about 2000 W from the lower part of the rig, below -134 mm.
- about 400 W for the upper part of the rig, from $Z = +166$ mm to $Z = +246$ mm.

Calculations indicate that the increase in sodium temperature inside the rig was $\sim 9^\circ\text{C}$, which is in quite good agreement with the measurements (see below). This increase comprised:

- about 3°C due to gamma heating inside the rig (where the thermal power due to gamma heating inside the rig is ~ 7151 W);
- about 6°C by thermal conduction and convection through the thermal gas shield.

The temperature of the specimens was believed to be very close to that of the sodium coolant.

5.4 Thermal Monitors

For each experiment, some fuse thermal monitors were placed among the specimens in several baskets at different levels. The thermal monitors are based upon a Mg-Zn eutectic. Two types of thermal monitors were used located at stages 1 and 3: a Mg-Zn alloy with a fusion temperature of $343 \pm 3^\circ\text{C}$ and Zn with a fusion temperature of $420 \pm 3^\circ\text{C}$. After the irradiation, the monitors were examined by X-ray radiography to check that there was no melting, thus assuring that temperature has been kept below 343°C during the whole experiment.

5.5 Monitoring of the Irradiation

From the beginning of the Boris experiment, there was a full on-line measurement of the irradiation conditions:

- the thermal power of the reactor;
- the primary sodium flow rate in the reactor (i.e. sum of the flow rates in the two primary sodium loops);
- the temperature of the primary sodium coolant at the inlet (this temperature is the average sodium temperature in both loops of the primary circuit weighted by the flow rate of each loop).
- for the instrumented D23 cell, the outlet temperature of sodium was measured by means of two thermocouples located inside the rig, at $Z = + 216 \text{ mm}$ and $Z = + 236 \text{ mm}$ (+ 50 and + 70 mm above the top of basket 7). The accuracy of the measurement of the temperature is about $\pm 2^\circ\text{C}$. Thermocouples were changed for each irradiation cycle. Usually, the temperatures given by the two thermocouples were very close ($\pm 1^\circ\text{C}$).

6

BORIS 6 AND 7 EXPERIMENTS

6.1 Description of the Materials and Specimens for the Boris 6 and 7 Experiments

Both industrial grades of stainless steel and experimental alloys with tailored additions of solute elements (see Tables 6-1 and 6-2) were irradiated. The types of specimens included tensile specimens, round compact tension (RCT) specimens and thin (~250 microns thick) 3mm diameter discs destined for metallurgical characterization studies. The specimens were supplied by Pacific Northwest National Laboratory (PNNL). The tensile specimens were 2 mm diameter in the gauge section (Figure A-1 in appendix A). The dimension of the reduced size RCT specimens are shown in Figure A-2. The 3 mm diameter discs for TEM investigations were contained in approximately 35 mm long capsules. The contents of the CIR capsules are given in Appendix B. Some flat tensile specimens (Figure A-3) supplied by the Argonne National Laboratory were also added to Boris 6 and 7. The list of materials and their chemical compositions are given in Tables 6-1 and 6-2. Their locations in Boris 6 and 7 are shown in Tables 6-3 to 6-8.

Boris 6 and 7 Experiments

Table 6-1

CIR Materials Irradiated in the Boris 6 and 7 Experiment: Chemical Composition (Weight %)

Material	Heat #	C	Mn	Si	P	S	Cr	Ni	Mo	N	Nb	Ti	O	Co	Cu	Hf
SA/CW304L SS Core Shroud	AS/AR	0.023	1.82	0.56	0.023	0.015	19.95	10.80	0.53	0.072	<0.001	0.02	0.011	0.22	0.29	
SA304L SS (Swedish)	SW	0.022	1.07	0.24	0.015	<0.002	18.42	10.45	—	0.025	—	—	—	—	—	
SA/CW/Des316 SS Baffle Bolt	BS/BR/BD	0.056	1.13	0.73	0.022	0.022	16.84	10.54	2.25	0.021	0.008	0.01	0.009	0.12	0.25	
CW316+Ti Stab. SS	CR	0.070	1.40	0.56	0.013	0.007	16.77	12.78	2.18	0.008	<0.01	0.38	0.004	0.10	0.06	
HP 304 SS	ES	0.021	0.94	0.04	<0.01	0.003	18.76	12.37	0.04	0.0003	0.005	0.01	0.004	0.01	<0.01	
HP 304 SS (-C)	FS	0.008	0.98	0.03	<0.01	0.003	18.17	12.06	0.02	0.0005	0.002	0.01	0.013	0.01	<0.01	
HP 304 SS (+Mo)	GS	0.020	0.97	0.03	<0.01	0.002	18.26	12.15	2.36	0.0004	0.003	0.01	0.005	0.01	0.01	
HP 304 SS (+Si)	HS	0.020	1.01	1.05	<0.01	0.002	18.17	12.45	0.02	0.0005	<0.001	0.01	0.007	0.01	<0.01	
HP 304 SS (+Ni)	KS	0.020	1.00	0.03	<0.01	0.002	18.21	25.08	0.02	0.0005	<0.001	0.01	0.003	0.01	<0.01	
HP 304 SS (Cr+Ni)	LS	0.020	1.02	0.03	<0.01	0.002	25.22	25.07	0.02	0.0005	<0.001	0.01	0.009	0.01	0.01	
HP 304 SS (+Ti)	MS	0.020	1.00	0.03	<0.01	0.003	18.03	11.22	0.02	0.0005	<0.001	0.30	0.011	0.73	<0.01	
HP 304 SS (+Nb)	NS	0.020	1.00	0.03	<0.01	0.003	18.24	12.12	0.02	0.0004	0.595	0.01	0.004	0.01	<0.01	
HP 316L (+Hf)	PS	0.028	1.01	0.10	0.01	0.007	17.03	13.60	2.18							1.17
HP 304 SS (-C+P)	I	0.007	1.01	0.03	0.016	0.003	18.21	12.11	0.02	0.0004	<0.001	0.01	0.012	0.01	<0.01	
TEM CIR packets																
HP 304 SS (+Si)	H	0.020	1.01	1.05	<0.01	0.002	18.17	12.45	0.02	0.0005	<0.001	0.01	0.007	0.01	<0.01	
HP 304 SS (+Mn-Ni)	J	0.020	9.95	0.03	<0.01	0.005	18.14	5.10	0.02	0.0006	<0.001	0.01	0.013	<0.01	<0.01	

SA = solution-annealed; CW = cold-worked at room temperature; Des =desensitized, SS = stainless steel; HP = high-purity.

Table 6-2

ANL-NRC Materials (Flat Tensile Specimens) Irradiated in the Boris 6 Experiment: Chemical Composition (Weight %)

	Material Type ^a	Heat ID	Material Code ^b	Ni	Si	P	S	Mn	C	N	Cr	Other Elements ^c
1	347 SA	316642	D1	10.81	0.29	0.023	0.014	1.56	0.030	0.021	18.06	Nb 0.60, Mo 0.29, Cu 0.09
2	347 CW	316642CW	D2	10.81	0.29	0.023	0.014	1.56	0.030	0.021	18.06	Nb 0.60, Mo 0.29, Cu 0.09
3	316 SA	2333	B1	8.50	0.65	0.031	0.029	1.38	0.035	0.068	18.30	Mo 0.37
4	316 CW	2333 CW	B2	8.50	0.65	0.031	0.029	1.38	0.035	0.068	18.30	Mo 0.37
5	316 LN SA	623	B3	10.33	0.70	0.007	0.002	0.97	0.019	0.103	17.23	Mo 2.38, Cu 0.21
6	316 LN-Ti SA	625	B4	10.31	0.72	0.007	0.002	0.92	0.012	0.064	17.25	Mo 2.39, Ti 0.027, Cu 0.21
7	316 SA	C21	B5	10.24	0.51	0.034	0.001	1.19	0.060	0.020	16.28	Mo 2.08, B <0.001
8	316 CW	C21 CW	B6	10.24	0.51	0.034	0.001	1.19	0.060	0.020	16.28	Mo 2.08, B <0.001
9	316 WW	C21 WW	B7	10.24	0.51	0.034	0.001	1.19	0.060	0.020	16.28	Mo 2.08, B <0.001
10	CF-3 cast SS	52	C1	9.40	0.92	0.012	0.005	0.57	0.009	0.052	19.49	Mo 0.35, δ 13.5%
11	CF-8 cast SS	59	C2	9.34	1.08	0.008	0.007	0.60	0.062	0.045	20.33	Mo 0.32, δ 13.5%
12	CF-3 cast SS	69	C3	8.59	1.13	0.015	0.005	0.63	0.023	0.028	20.18	Mo 0.34, δ 23.6%
13	CF-8 cast SS	68	C4	8.08	1.07	0.021	0.014	0.64	0.063	0.062	20.64	Mo 0.31, δ 23.4%
14	304 SA	C1	A1	8.12	0.50	0.038	0.002	1.00	0.060	0.060	18.11	B 0.001
15	304 SA	C9	A2	8.75	0.39	0.013	0.013	1.72	0.062	0.065	18.48	B <0.001
16	304 SA	C12	A3	8.23	0.47	0.018	0.002	1.00	0.060	0.070	18.43	B <0.001
17	304 CW	C1 CW	A4	8.12	0.50	0.038	0.002	1.00	0.060	0.060	18.11	B <0.001
18	304 CW	C12 CW	A5	8.23	0.47	0.018	0.002	1.00	0.060	0.070	18.43	B <0.001
19	304 GBE	304 GBE	A6	8.43	0.46	0.014	0.003	1.54	0.065	0.088	18.38	Mo 0.51, Co 0.22
20	316 GBE	316 GBE	B8	11.12	0.57	0.011	0.022	1.85	0.070	0.056	16.57	Mo 2.27, Co 0.10
21	690 GBE	690 GBE	E1	59.40	0.30	—	0.003	0.42	0.010	—	29.10	Fe 10.26
22	304 BASE	304 BASE	A7	8.46	0.41	0.013	0.014	1.56	0.065	0.086	18.32	Mo 0.36, Co 0.12
23	316 BASE	316 BASE	B9	10.30	0.43	0.013	0.020	1.53	0.055	0.054	16.42	Mo 2.19, Co 0.10
24	690 BASE	690 BASE	E2	61.49	0.05	—	<0.01	0.15	0.030	—	29.24	Fe 9.02
25	HP 304L SA	945	A8	9.03	0.03	<0.005	0.005	1.11	0.005	0.003	19.21	O 0.047, Mo <0.005
26	HP 304L SA	1327	A9	9.54	0.01	0.001	0.002	1.12	0.006	<0.001	19.71	O 0.008, Mo 0.02
27	304L SA	C3	A10	8.91	0.46	0.019	0.004	1.81	0.016	0.083	18.55	B <0.001
28	304L CW	C3 CW	A11	8.91	0.46	0.019	0.004	1.81	0.016	0.083	18.55	B <0.001
29	304-like alloy	L5	A12	9.66	0.90	0.113	0.028	0.47	0.006	0.033	21.00	B <0.001

^aSA = solution-annealed; CW = cold-worked at room temperature; WW = warm-worked at 400°C;

SS = stainless steel; GBE = grain-boundary-engineered; BASE = base heat for GBE modification; HP = high-purity.

^bA = Type 304 SS, B = Type 316 SS, C = cast SS, and D = Type 347 SS; E = Alloy 690.^c δ = ferrite content

Boris 6 and 7 Experiments

Table 6-3
List and Location of the CIR and ANL Specimens Irradiated in the Boris 6R1-1 Experiment

Basket	Elevation (mm)	Damage Dose (dpa)	Material	Specimen		
				Tensile (GI 116)	CTR	Other
7	166 108	5.4	SA304L SA316 HP304	AS11, AS12, AS13, AS14 BS11, BS12, BS13 ES17	AS01 BS01	ANL 5-1 (D1-1, D2-1, D2-2, B3-1) ANL 5-2 (A5-1, A6-1, B8-1, E1-1) ANL 5-3 (B4-1, B5-1, B6-1, B6-2) TEM AN05 TEM C5A
6	108 72	6.3				Monitor 343°C
5	72 36	25.0	CW316 CW316Ti	B124, B125, B126 CR15, CR16, CR17, CR18, CR19	BR02 CR02	TEM 6002 (JOBB) TEM C20A
4	36 0	25.9	SA316 SA304L HP304	BS17, BS18 AS20, AS21, AS22, AS23 ES18	BS03 AS03	ANL 20-1 ANL 20-2 ANL 20-3 ANL 20-4 TEM C20B Dosimeter
3	0 -36	26.2				ANL 40-3 Monitor 420°C
2	-36 -72	25.7				ANL 40-2
1	-72 -134	24.5				ANL 40-1 TEM AN40 Monitor 343°C

Table 6-4

List and Location of the Specimens in Baskets 6 and 7 Irradiated in the Boris 6R1-2 Experiment. The Specimens in Baskets 1 to 5 are the same as those in Boris 6R1-1

Basket	Elevation (mm)	Damage Dose (dpa)	Material	Specimen		
				Tensile (GI 116)	CTR	Other
7	166 108	10.3	SA304L	AS15, AS16, AS17, AS18, AS19 BS14, BS15, BS16 ES16	AS02, AS03	ANL 10-1 (D1-2, D1-3, D2-3, D2-4) ANL 10-4 (B4-2, B4-3, B3-2, B3-3) TEM AN10 TEM CIR10A
			SA316 HP304		BS02	
6	108 72	11.9	HP304	ES11, ES12, ES13, ES14 GS11, GS12, GS13, GS14	ES01	ANL 10-2 (B1-1, B1-2, B2-1, B2-2) ANL 10-3 (B5-2, B5-3, B5-4, B6-3) TEM capsule: He10 TEM capsule CIR10B Monitor 343°C ANL 10-2 (B1-1, B1-2, B2-1, B2-2)
			316BB		GS01	

Boris 6 and 7 Experiments

Table 6-5**List and Location of the Specimens Irradiated in the Boris 6R1-3 Experiment****The Specimens in Baskets 1 to 5 are the same as those in Boris 6R1-1 and 6R1-2**

Basket	Elevation (mm)	Damage Dose (dpa)	Material	Specimen		
				Tensile (GI 116)	CTR	Other
7	166	4.7	CW316	BR13, BR14, BR15, B130, B131	BR01	ANL 5-4 (A7-1, B9-1, E2-1, A8-1) ANL 5-5 (A1-1, A2-1, A3-1, A4-1) ANL 5-6 (A9-1, A10-1, A11-1, A12-1) TEM C5B
	108		SS316 Ti HP304	CR11, CR12, CR13, CR14 ES15	CR01	
6	108 72	5.4	CW316	B122, B123		Monitor 343°C

N. B.: ANL specimens 10-5 (B6-4, B6-5, B7-1, B7-2) and 10-6 (C1-1, C1-2, C2-1, C2-2) were placed in a second irradiation rig (basket 7) with similar irradiation conditions (dose: 10.4 dpa).

Table 6-6

List and Location of the CIR and ANL Specimens Irradiated in the Boris 7-1 Experiment

Basket	Elevation (mm)	Damage Dose (dpa)	Material	Specimen		
				Tensile (GI 116)	CTR	Other
7	166 108		HP 304 (Cr+Ni) Des 316 CW 316 SS 316 Ti	BD11, BD12	LS01 BD01 BR04 CR04	
			HP 304 (+Mo) HP 304 (+Si) HP 316L (+Hf)	GS15 HS11, HS12, HS13 PS11, PS12		
6	108 72		HP 304 (-C) HP 304 (+Mo) HP 304 (+Si) HP 304 (Cr+Ni)	FS11, FS12, FS13 LS11, LS12, LS13	FS01 GS02 HS01	ANL A5.1, A11.2, A3.2, A1.2 TEM 6002 (JOB B) TEM C20A TEM CIR IIA
			HP 316L (+Hf) HP 304 (+Ni)	PS13, PS14, PS15 KS11, KS12, KS13		
5	72 36		HP 316L (+Hf) HP 304 (+Ni)	PS13, PS14, PS15 KS11, KS12, KS13	PS01, PS02 KS01	TEM CIR IIB TEM ANLW20 ANL A9.2, B8.2, A7.2, E2.2
4	36		SA316 SA304L	BS17, BS18 AS20, AS21, AS22, AS23 ES18	BS03 AS03	ANL 20-1 ANL 20-2 ANL 20-3 ANL 20-4 TEM C20B Dosimeter
	0		HP304			
3	0 -36					ANL 40-3 Monitor 420°C
2	-36 -72					ANL 40-2
1	-72 -134					ANL 40-1 TEM AN40 Monitor 343°C

Boris 6 and 7 Experiments

Table 6-7

List and Location of the Specimens in Baskets 5, 6 and 7 Irradiated in the Boris 7-2 Experiment. The Specimens in Baskets 1 to 4 are the same as those in Boris 7-1 (in Basket 4 only Specimen BS03 was Removed et Replaced with Specimen SW02)

Basket	Elevation (mm)	Damage Dose (dpa)	Material	Specimen		
				Tensile (GI 116)	CTR	Other
7	166 108					
6	108 72			MS11, MS12 NS11, NS12 CR22 SW30, SW31, SW32, SW33 ES21	MS01 NS01	TEM ANLW20 TEM 6002 (JOB B) TEM C20A TEM CIR IIA
5	72 36		Swed. SA304L	SW34, SW35 IP11, IP12	BR03 SW01	
4	36 0		SA316 SA304L HP304 Swed. SA304L	BS17, BS18 AS20, AS21, AS22, AS23 ES18	AS03 SW02	ANL 20-1 ANL 20-2 ANL 20-3 ANL 20-4 TEM C20B Dosimeter

Table 6-8

List and Location of the Specimens Irradiated in the Boris 7-3 Experiment. The Specimens in Baskets 1 to 4 and 6 and 7 are the same as those in Boris 7-2

Basket	Elevation (mm)	Damage Dose (dpa)	Material	Specimen		
				Tensile (GI 116)	CTR	Other
5	72 36		Swed. SA304L	SW36, SW37 IP11, IP12	BR03 IP01	

6.2 Irradiation Conditions for the Boris 6 and 7 Experiments

The Boris 6 irradiation covered the period June 26, 2001 to March 10, 2003 including 8 irradiation sub-cycles (73 to 76A) and several long shut-down periods for reactor maintenance. During these irradiation sub-cycles, the test rig loaded with the specimens was irradiated in the fifth row of the core of the Bor-60 reactor (most of the time in the instrumented D23 cell). The main irradiation conditions are given at Table 6-9.

The Boris 7 irradiation covered the period March 20, 2003 to May 23, 2004 including 6 irradiation sub-cycles (76B to 78B). During these irradiation sub-cycles, the test rig loaded with the specimens was irradiated in the fifth row of the core of the Bor-60 reactor (most of the time in the instrumented D23 cell). The main irradiation conditions are given at Table 6-10.

6.2.1 Neutron Monitoring

Boris 6: Two upper baskets (levels 6 and 7) of the rig were unloaded after irradiation cycle 73-A after the specimens had reached at least 5 dpa: the actual damage was 5.3 dpa at level 7 and 6.3 at level 6. These baskets were then reloaded with fresh specimens and subsequently irradiated to at least 10 dpa. In fact, these two baskets were unloaded after sub-cycle 75-A with the actual irradiation damage at 10.3 dpa for level 7 and 11.9 dpa for level 6. Finally, these two uppermost baskets were again reloaded with fresh specimens to achieve 4.7 dpa at level 7 and 5.4 dpa at level 6. By the end of the Boris 6 experiment, the total irradiation damage was between 24.5 dpa and 26.2 dpa for specimens located in the lower levels of the irradiation rig. The damage rate at the central plane of the rig (baskets 3-4) was $\sim 7 \times 10^{-7}$ dpa/s; the damage (dpa-NRT) for each sub-cycle and each basket is given in Table 6-11.

Boris 7: Three upper baskets (levels 5, 6 and 7) of the rig were unloaded after irradiation cycle 77-A after the specimens had reached about 10 dpa: the actual damage was 7.8 dpa at level 7, 9.1 at level 6 and 9.6 at level 5. These baskets were then reloaded with fresh specimens and subsequently irradiated to about 5 dpa (5.6 dpa at level 7). Finally, the uppermost basket was again reloaded with fresh specimens to achieve 3.6 dpa at level 7. By the end of the Boris 7 experiment, the total irradiation damage was up to 47.5 dpa for specimens located in Boris 6 and Boris 7 experiments. The damage rate at the central plane of the rig (baskets 3-4) was $\sim 7 \times 10^{-7}$ dpa/s; the damage (dpa-NRT) for each sub-cycle and each basket is given in Table 6-12.

6.2.2 Temperature Monitoring

The temperature of sodium coolant was $\sim 315^\circ\text{C}$ at the inlet and $\sim 325^\circ\text{C}$ at the outlet (Figure 6-1). The increase of temperature of sodium in the rig ($T_{\text{outlet}} - T_{\text{inlet}}$) varied from ~ 8 to $\sim 11^\circ\text{C}$ (averaged over a cycle). These variations are attributed to:

- variation in thermal power and primary sodium coolant flow rate;
- variation in the burn-up of the six surrounding cells. An increase in burn-up results in an increase of the temperature of the fuel assembly;
- possible modifications to the thermal gas shield during handling of the rig.

Boris 6 and 7 Experiments

Thermal fuse monitors from the Boris 6 and 7 experiments were analysed; no melting was detected.

Table 6-9
Irradiation Conditions for the Boris 6 Experiment

Sub-cycle	73	73a	74*	74a*	75	75a	76	76a
Beginning of the sub-cycle	26.06.01	21.08.01	13.01.02	13.03.02	28.06.02	20.08.02	25.11.02	11.02.03
End of the sub-cycle	12.08.01	21.10.01	26.02.02	12.05.02	07.08.02	15.10.02	15.01.03	10.03.03
Number of fuel:								
- fuel assemblies	100	103	107	111	111	112	106	108
- blanket	7	7	6	6	6	6	6	6
Average power of Bor-60 (MWt)	41.7	43.3	35.1	44	40.7	50.6	51.3	51.3
Duration of the cycle (efficient days)	47	61	44	60	41	56	50	27
Total power over the cycle (MWt*h)	47015	63650	37050	63197	40025	68340	61611	33242
Total power over the experiment (MWt*h)	47015	110665	147715	210912	250937	319277	380888	414130
Mean sodium flow-rate (m ³ /h)	911	888	1010	999	985	993	987	992
Neutron flux (calculated by RIAR for the cells, at 55 MWt):								
- $10^{15} \text{ s}^{-1} \text{ cm}^{-2}$ (E>0 MeV)	2.46	2.38	2.31	2.30	2.29	2.41	2.27	2.29
- $10^{15} \text{ s}^{-1} \text{ cm}^{-2}$ (E>0,1 MeV)	1.92	1.84	1.81	1.79	1.78	1.88	1.78	1.79
-Damage rate for steel, calculated by RIAR for D23 (B23*) at 55MWt, ($10^{-7} \text{ dpa.s}^{-1}$)	9.3	9.0	8.8	8.7	8.7	9.2	8.7	8.8
Axial distribution of damage over the 7 stages, calculated by RIAR for the cell (max/average)	1.095	1.099	1.099	1.099	1.098	1.096	1.099	1.099
Fuel burn-up:								
- average over the core	6.7	7.4	5.8	5.8	6.6	7.1	5.8	6.0
- around the cell	5.9	6.6	8.1	8.6	9.5	10.1	5.5	6.4
Mean measured temperature of sodium at the inlet (°C):	312.7	314.4	313.6	311.2	317.7	316.4	311.8	310.8
Mean measured temperature of sodium at the outlet (°C):	322.6	325.9	322.2	320.4	327.2	327.9	322.9	321.3
Mean temperature increase in the capsule (°C):	9.8	11.6	8.6	9.2	9.6	11.5	11.1	10.5

Boris 6 and 7 Experiments

Table 6-10
Irradiation Conditions for the Boris 7 Experiment

Cycle	76B	77	77A	78	78A	78B
Beginning of the cycle	20.03.03	26.06.03	01.09.03	24.11.03	23.01.04	24.03.04
End of the cycle	11.05.03	16.08.03	12.10.03	12.01.04	14.03.04	23.05.04
Number of fuel:						
- fuel assemblies	109	107	108	107	108	111
- blanket	6	4	4	4	3	3
Average power of Bor-60 (MWt)	46	45	48	50	51	51
Duration of the cycle (efficient days)	52	51	41	44	50	60
Total power over the cycle (MWt*h)	57442	54885	46941	52753	61118	73284
Total power over the experiment (MWt*h)	57442	112327	159268	212021	273139	346423
Mean sodium flow-rate (m³/h)	975.9	921.9	993.0	1054.4	1038.9	1055.6
Neutron flux (calculated by RIAR for the cell, at 55 MWt):						
- 10 ¹⁵ c ⁻¹ cm ⁻² (E>0 MeV)	2,32	2,41	2,37	2,37	2,29	2,32
- 10 ¹⁵ c ⁻¹ cm ⁻² (E>0,1 MeV)	1,78	1,89	1,85	1,85	1,78	1,81
-Damage rate for steel, calculated by RIAR for the cell at 55MWt, 10⁻⁷ dpa*c⁻¹	8,7	9,3	9,0	9,0	8,7	8,8
Axial distribution of damage over the 7 stages, calculated by RIAR for the cell (max/average)	1,1	1,1	1,1	1,1	1,1	1,1
Fuel burn-up, % h.a.:						
- average over the core	6,3	5,5	6,2	5,7	6,3	6,9
- around the cells	9,0	7,6	8,3	6,2	6,9	7,7
Mean measured temperature of sodium at the inlet (°C):	310.9	313.8	310.2	312.6	314.7	314.5
Mean measured temperature of sodium at the outlet (°C):	320.7	324.2	320.2	322.5	324.3	324.3
Mean temperature increase in the capsule (°C):	9.8	10.4	10.0	9.9	9.6	9.8

Table 6-11
Boris 6: Damage (dpa-NRT*) for each Specimen Basket

“Segment”	Cycle	Basket						
		1	2	3	4	5	6	7
« 5dpa »	Cycle 73	2.8	2.9	3.0	2.9	2.8	2.7	2.3
	Cycle 73-A	3.8	4.0	4.0	4.0	3.8	3.6	3.1
« 10 dpa »	Cycle 74	2.2	2.3	2.3	2.3	2.2	2.1	1.8
	Cycle 74-A	3.7	3.9	4.0	3.9	3.8	3.6	3.1
	Cycle 75	2,4	2,5	2,5	2,5	2,4	2,3	2,0
	Cycle 75-A	4.0	4.2	4.3	4.3	4.1	3.9	3.4
« 5dpa »	Cycle 76	3.7	3.8	3.9	3.8	3.7	3.5	3.0
	Cycle 76-A	2.0	2.1	2.1	2.1	2.0	1.9	1.7
Total		24.5	25.7	26.2	25.9	25.0	23.5	20.5

Table 6-12
Boris 7: Damage (dpa-NRT*) for each Specimen Basket

“Segment”	Cycle	Basket						
		1	2	3	4	5	6	7
« 10dpa »	Cycle 76-B	3.4	3.6	3.6	3.6	3.5	3.3	2.8
	Cycle 77	3.3	3.4	3.5	3.4	3.3	3.1	2.7
	Cycle 77-A	2.8	2.9	3.0	2.9	2.8	2.7	2.3
« 5 dpa »	Cycle 78	3.1	3.3	3.3	3.3	3.2	3.0	2.6
	Cycle 78-A	3.6	3.8	3.9	3.8	3.7	3.5	3.0
« 5dpa »	Cycle 78-B	4.3	4.6	4.6	4.6	4.4	4.2	3.6
Total		20.5	21.5	21.9	21.6	20.9	19.7	17.0

Boris 6 and 7 Experiments

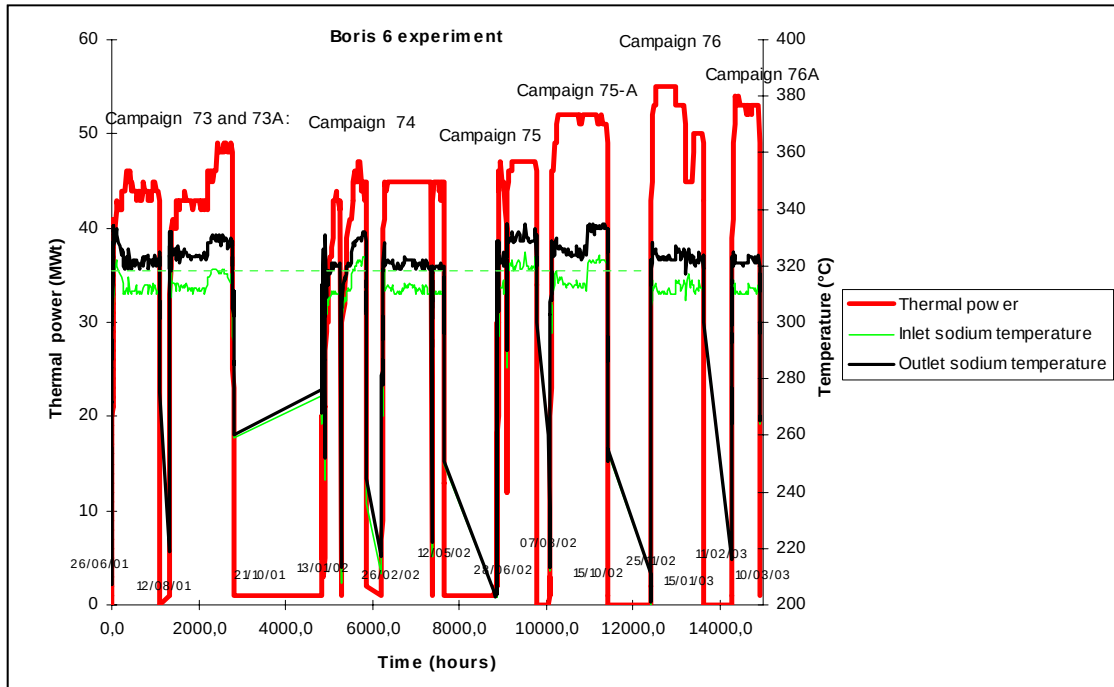


Figure 6-1
Thermal Power and Sodium Temperature Measured during the Boris 6 Experiment

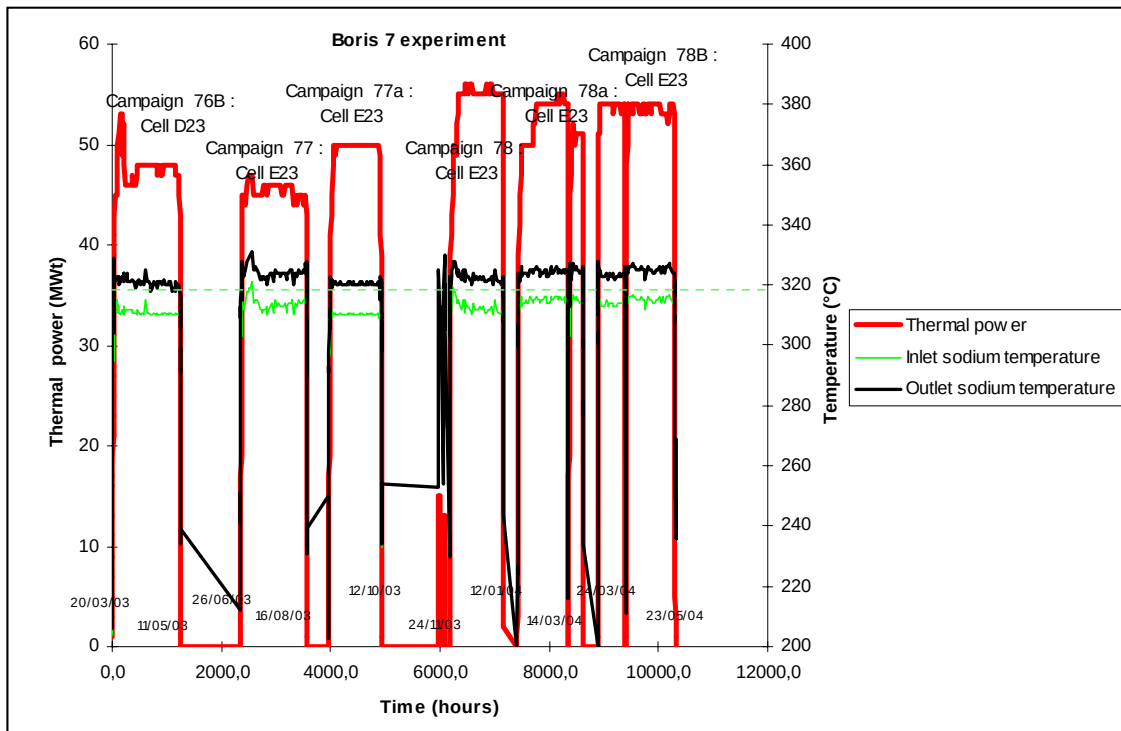


Figure 6-2
Thermal Power and Sodium Temperature Measured during the Boris 7 Experiment

6.3 Specimens Available for Post Irradiation Tests

- Crack Growth Tests will be performed on RCT specimens by Studsvik (Sweden) or other laboratories. Following the Boris 6 experiment, the available specimens for Crack Growth Tests are given in Table 6-13. They were shipped to Studsvik. Following the Boris 7 experiment, the available specimens for Crack Growth Tests are given in Table 6-14. They are available for shipment.
- Conventional tensile tests are performed by RIAR on two specimens per material and irradiation dose combination. Specimens for tensile tests are given in Table 6-15 (Boris 6) and Table 6-16 (Boris 7) in bold types. Other specimens (for possible SSRT tests) are also given in these two tables.
- TEM capsules available after Boris 6 and 7 are given in Table 6-17 and 6-18.

Table 6-13

List of RCT Specimens Available for Crack Growth Tests After Boris 6

Specimens	Damage Dose (dpa)	Date out of Reactor
AS04	< 10	Oct-02
AS02	10.2	Oct-02
AS01	5.5	Oct 01
BS02	10.2	Oct-02
BS01	5.5	Oct 01
BR02	25	March 03
BR01	4.8	March 03
CR02	25	March 03
CR01	4.8	March 03
ES01	11.8	Oct-02
GS01	11.8	Oct-02

Boris 6 and 7 Experiments

Table 6-14

List of RCT Specimens Available for Crack Growth Tests After Boris 7

Specimens	Damage Dose (dpa)	Date out of Reactor
AS03	47.5	june 04
BS03	35.0	Oct 03
BR04	7.8	Oct 03
BR03	11.3	june 04
BD01	7.8	Oct 03
CR04	7.8	Oct 03
LS01	7.8	Oct 03
FS01	9.1	Oct 03
GS02	9.1	Oct 03
HS01	9.1	Oct 03
KS01	9.6	Oct 03
MS01	10.7	june 04
NS01	10.7	june 04
PS01, PS02	9.6	Oct 03
SW01	6.9	March 04
SW02	11.2	june 04
IP01	4.4	june 04

Table 6-15

List of Tensile* and SSRT Specimens Available After Boris 6

Tensile Specimens	Damage Dose (dpa)	Date out of Reactor (BORIS 6)
AS11*-12*-13-14	5.5	Oct 01
AS15*-16*-17-18--19	10.2	Oct-02
BS11*-12*-13	5.5	Oct 01
BS14*-15*-16	10.2	Oct-02
BR13*-14*-15	4.8	March 03
B124-125-126	25	March 03
CR11*-12*-13-14	4.8	March 03
CR15*-16*-17-18-19	25	March 03
ES15*	4.8	March 03
ES17*	5.5	Oct 02
ES11*-12*-13-14	11.8	Oct-02
ES16	10.2	Oct-02
GS11*-12*-13-14	11.8	Oct-02
5-1, 5-2, 5-3 (ANL mat code: A5, A6, B3, B4, B5, B6, B8, D1, D2, E1)	5.5	Oct 01
10-1, 10-4 (ANL mat code: B3, B4, D1, D2)	10.2	Oct 01
10-2, 10-3 (ANL mat code: B1, B2, B5, B6)	11.8	Oct 01
10-5, 10-6 (ANL mat code: B6, B7, C1, C2)	10.4	June 01
5-4, 5-5, 5-6 (ANL mat code: A1, A2, A3, A4, A7, A8, A9, A10, A11, A12, B9, E2)	4.8	Oct-02

* Specimens shown in bold type have been selected for tensile tests at RIAR.

Table 6-16
List of Tensile* and SSRT Specimens Available After Boris 7

Tensile Specimens	Damage Dose (dpa)	Date out of Reactor (Boris 7)
SW34, SW35	6.9	March 03
GS 15	7.8	Oct 03
BD11- BD12	7.8	Oct 03
HS11-HS12-HS13	7.8	Oct 03
PS11- PS12	7.8	Oct 03
FS 11-FS12-FS13	9.1	Oct 03
LS11-LS12-LS13	9.1	Oct 03
PS 13-PS14-PS15	9.6	Oct 03
KS11-KS12-KS13	9.6	Oct 03
SW36, SW37	4.4	June 04
SW30, SW31, SW32, SW32	10.7	June 04
MS11, MS12	10.7	June 04
NS11, NS12	10.7	June 04
CR22	10.7	June 04
ES21	10.7	June 04
IP11, IP12	11.3	June 04
AS20, AS21, AS22, AS23	47.5	June 04
BS17, BS18,	47.5	June 04
ES18	47.5	June 04
ANL 40-1	45	June 04
ANL 40-2	47.2	June 04
ANL 40-3	48.1	June 04
ANL 20-1, 20-2, 20-3, 20-4	47.5	June 04
ANL A5-2, A11-2, A3-2, A1-2	9.1	Oct 03
ANL A9-2, B8-2, A7-2, E2-2	9.6	Oct 03

* Specimens shown in bold type have been selected for tensile tests at RIAR.

Boris 6 and 7 Experiments

Table 6-17
List of TEM Capsules Available After Boris 6

TEM Capsules Specimens	Damage Dose (dpa)	Date out of Reactor (BORIS 6)
CIR 5A	5.5	Oct 01
CIR 5B	4.8	March 03
AN 05	5.5	Oct-01
CIR 10A	10.2	Oct-02
CIR 10B	11.8	Oct-02
AN 10	10.2	Oct-02
He 10	11.8	Oct-02
AN 20	24.5	March 03

Table 6-18
List of TEM Capsules Available After Boris 7

TEM Capsules Specimens	Damage Dose (dpa)	Date out of Reactor (BORIS 7)
6002 (JOBB)	66	June 04
TEMC20A	46	June 04
TEMC20B	47.5	June 04
CIR IIA	19.7	June 04
CIR II B	9.9	Oct 03
TEM AN40	45	June 04
ANLW20	19.7	June 04

7

TENSILE TESTS RESULTS

In this chapter, a short description of the tensile test method and a preliminary analysis of the results are given.

7.1 Method

Tensile tests were carried out at RIAR in air at 330°C (close to the irradiation temperature: 320°C) in a hot cell using the same test equipment for both irradiated and unirradiated materials. The gage section of the tensile specimens was 2 mm diameter (type GI-116 as shown in Appendix A, Figure A-1). However, most of the tensile specimens did not conform to the drawing in Figure A-1 due to the reduced width of the heads. Due to this dimensional problem, as many as possible had been substituted with EDF fabricated specimens from the same heat of material during the first loading of the irradiation rig. In practice, this meant that specimens from material BR were substituted with specimens B that come from exactly the same heat of material in the as-received condition.

The tensile tests are done using conventional electromechanical tensile equipment made by Ismeritel. Extensometers produced by RIAR were used to measure elongation in some of the tests. They consist of 2 rigid arms linked by a flexible strip equipped with bonded resistance strain gages and are capable of working at temperatures up to 400°C. The extensometer was fixed against the heads of the specimens. However, where the tensile specimens did not conform exactly to the EDF drawing (due to the reduced size of the heads and the associated risk that they would rupture at the pin holes if tested in the classical manner), specimen grips were adapted to pull on the specimen shoulders. In this case, extensometry directly on the specimen gage length was precluded (see Figure C-3).

The tests at 330°C were carried out in an electric resistance furnace. The crosshead displacement rate was 0.2 mm min^{-1} , which corresponds to a strain rate of $3 \times 10^{-4} \text{ s}^{-1}$ in the test section of the specimen. The extensometer, load cell and cross head displacement signals were recorded using a computerized data storage system.

After the test, the conventional mechanical strength parameters were estimated from the recorded stress/strain curves according to NF EN 10002-5: yield stress (at 0.2 % plastic strain), ultimate tensile stress and total elongation. Plastic strain at maximum load was also estimated (uniform elongation). This analysis is performed by RIAR. An independent check made by CEA and EDF gave very similar results. Reduction of area is estimated from photographs of the broken specimens taken in hot cell.

Tensile Tests Results

The tensile test methods used at RIAR, EDF and CEA have also been compared. In this case, tensile test were done at room temperature and the results obtained in the different laboratories were consistent.

7.2 Results

Tensile tests were performed on the specimens as indicated in Table 6-15 and 6-16. The conventional parameters (yield stress: YS, ultimate tensile strength: UTS, uniform elongation: UE and total elongation: TE) are given in Table 7-1 and 7-2 and 7-3 and the whole curves in appendix C.

The engineering tensile curves are typical of austenitic stainless steels irradiated at low temperature: very high yield strength, very little strain hardening and early necking. Nevertheless the reduction of area is not strongly affected by irradiation and remains very high.

7.2.1 Commercial Grades

Comparison of the tensile results were made on specimens BR13, BR14, B130 and B131, all from the same heat and irradiated at 4.8 dpa, but with different specimen head geometry, shows similar results (Table 7-1). Thus, no significant consequence has been observed in tensile properties due to the difference in the design of the specimen heads and previous tensile data concerning B material were supplied for irradiation at 9.6, 17.7 and 42 dpa.

A comparison has been also made between BS and BR that originate from the same heat of Type 316 stainless steel although the first one is supposed to be solution annealed and the second one cold worked. Results clearly indicate that what is referred to as the BS condition is not solution annealed. The solution annealed condition should have a yield strength in the low 200s MPa, similar to AS or BD whereas BS has a yield strength of 880 MPa. So BS is most likely highly cold worked (40%) and BR or B is moderately cold worked (15%). Neither are in the solution annealed condition. Nevertheless, tensile data on material B effectively Solution Annealed are available from a private EDF program (Table 7-4).

CR material (titanium stabilised cold worked 316) also shows high YS and UTS values both in unirradiated and irradiated conditions indicating high initial cold working (YS = 740 MPa for unirradiated materials, that is about 30% cold working).

As expected, saturation of the tensile characteristics is reached from 5-10 dpa and the saturation values evidently depend on the materials (higher for cold-worked 316/316L steels than for solution-annealed 304L steels) but it depends also on chemical composition: the saturation level is much less important for SW material (YS = 640 MPa) than for AS material (YS = 870 MPa) both solution annealed, may be partly due to the lower silicon content of SW (0.24% instead of 0.56%).

Even if their saturation yield strength is lower, hardening is more significant with solution-annealed 304 steels (around 650 MPa) than with cold-worked 316 steels (around 450 MPa), consistently with what is usually noticed [4].

The best fit to adjust the dose (in dpa) dependence from experimental tensile data is with the exponential type laws set out below:

$$F(\text{dpa}) = F_{\text{initial}} + [F_{\text{saturation}} - F_{\text{initial}}] \cdot [1 - \exp - (\text{dpa}/\text{dose constant})]$$

Where: $F(\text{dpa})$ represents the value examined ($R_{p0.2}$, R_m , A_u , A_t , Z) for the dose received by the material;

- F_{initial} represents the value of F in the non irradiated state;
- $F_{\text{saturation}}$ represents the saturation value;

the dose constant characterises the “rate of degradation” and is close to 3 dpa.
7.2.2 Tailored Alloys

After irradiation up to about 10 dpa, comparisons were made between the reference high purity 304 base material (ES) and the different tailored materials (GS, FS, HS, KS, MS, NS and IP Figures 7-5 to 7-7). Comparison with PS material (Hf added) is difficult as it was not prepared from the same HP 304 heat. Unfortunately comparisons can be made only on irradiated materials and not on unirradiated materials as the number of tensile specimens was not sufficient for tests on unirradiated specimens.

The yield strength values for HP 304 base material (ES) are in the range of values for commercial 304 grades. The addition of silicon (HS) and at a lesser extend of molybdenum (GS) lead to the higher YS level (respectively 830 MPa and 740 MPa), as the decrease in carbon content leads to the lower YS level after irradiation (595 MPa). It is consistent with the literature data asserting that the effect of carbon is to increase the hardening effect of Frank loops and that the addition of silicon (around 1%) appears to significantly increase the density of the dislocation loops and therefore the associated hardening¹. As for molybdenum, no clear evidence of hardening effect is found in the literature.

Additions of Ti (MS) and Nb (NS) seem to play the same role: they significantly decrease irradiation induced hardening compared to base alloy. It is found in the literature that, “large” solute atoms (Ti, Nb, etc.) act as annihilation sinks for the irradiation point defects and then reduce the size of the dislocation loops and then reduce irradiation hardening¹. Addition of nickel (KS) seems also to play a similar role, decreasing irradiation induced hardening, but in the literature nickel’s effect is still controversial.

¹ Since the irradiation induced hardening is essentially due to faulted Frank loops, it can be expressed as follows:
 $\Delta\sigma = M\alpha_{\text{loops}}\mu b\sqrt{\rho_{\text{loops}}\phi_{\text{loops}}}$ where M is the Taylor factor, ϕ_{loops} the diameter of the Frank loops, ρ_{loops} the density of Frank loops and α_{loops} the obstacle force of Frank loops, μ the shear modulus and b the Burgers vector.

Tensile Tests Results

Addition of Molybdenum (GS) or addition of Phosphorous (with decrease of carbon, IP) lead to the higher uniform elongation after irradiation (respectively 0.4 and 0.5%). As for total elongation, no significant differences were noted for the tailored materials.

Comparison of the yield strength data for these neutron irradiations (after about 10 dpa) to the proton irradiation hardness data (after about 5 dpa) for the same alloys coming out of the CIR program are presented on Figure 7-8 using the conversion formula to go from Yield strength to Hardness developed in [5]. Except for KS material (Ni added) for which hardening is significantly higher after proton irradiation than after neutron irradiation (without evident explanation), results are satisfactorily consistent. Then these results confirm that proton irradiation could be a efficient way to reproduce neutron irradiation.

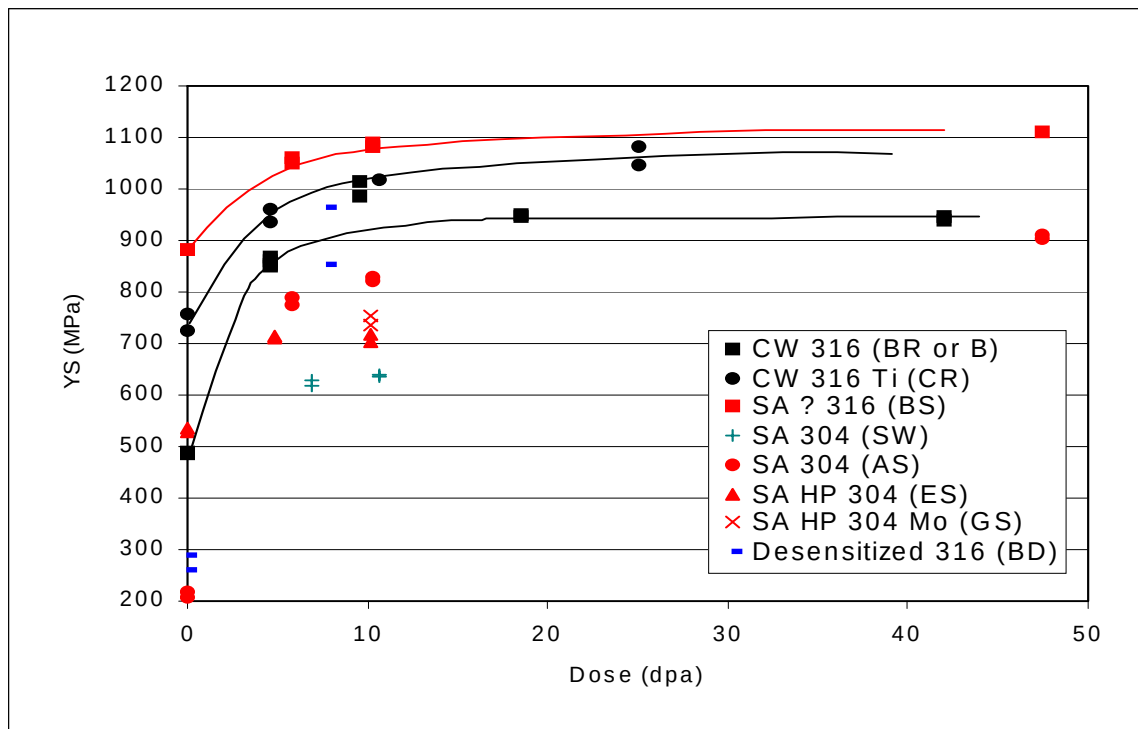


Figure 7-1
Yield Stress (at 330°C) as a Function of Damage Dose

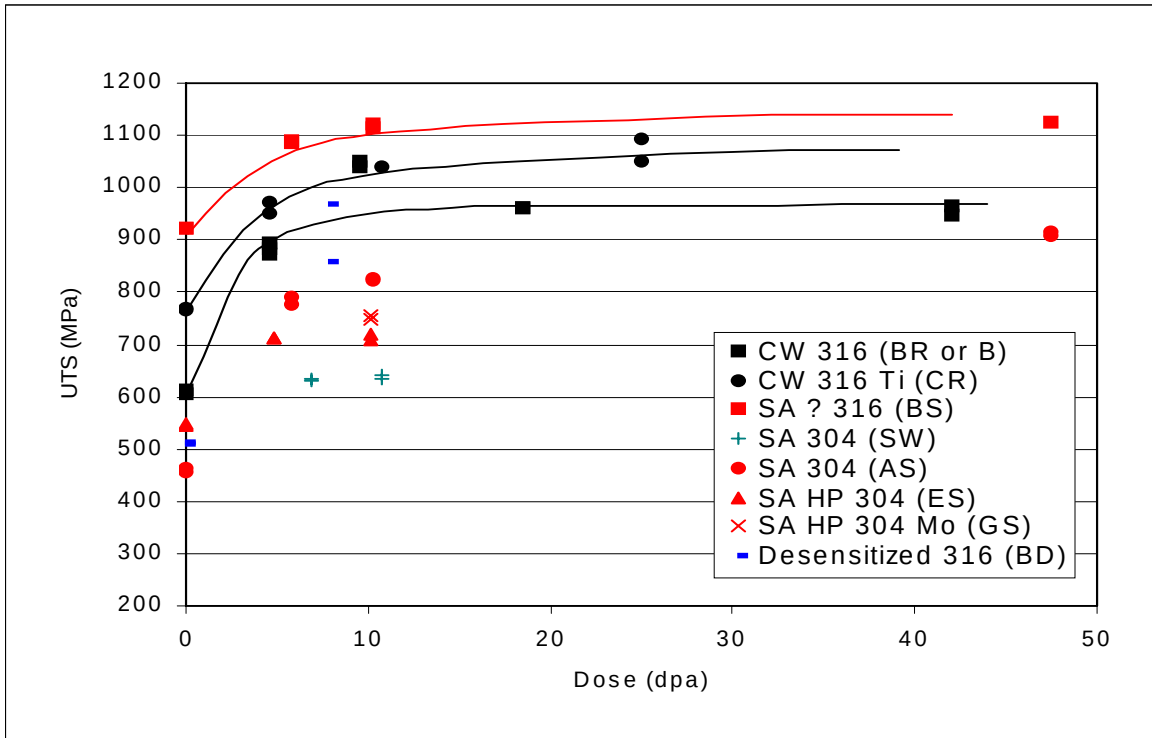


Figure 7-2
Ultimate Tensile Strength (at 330°C) as a Function of Damage Dose

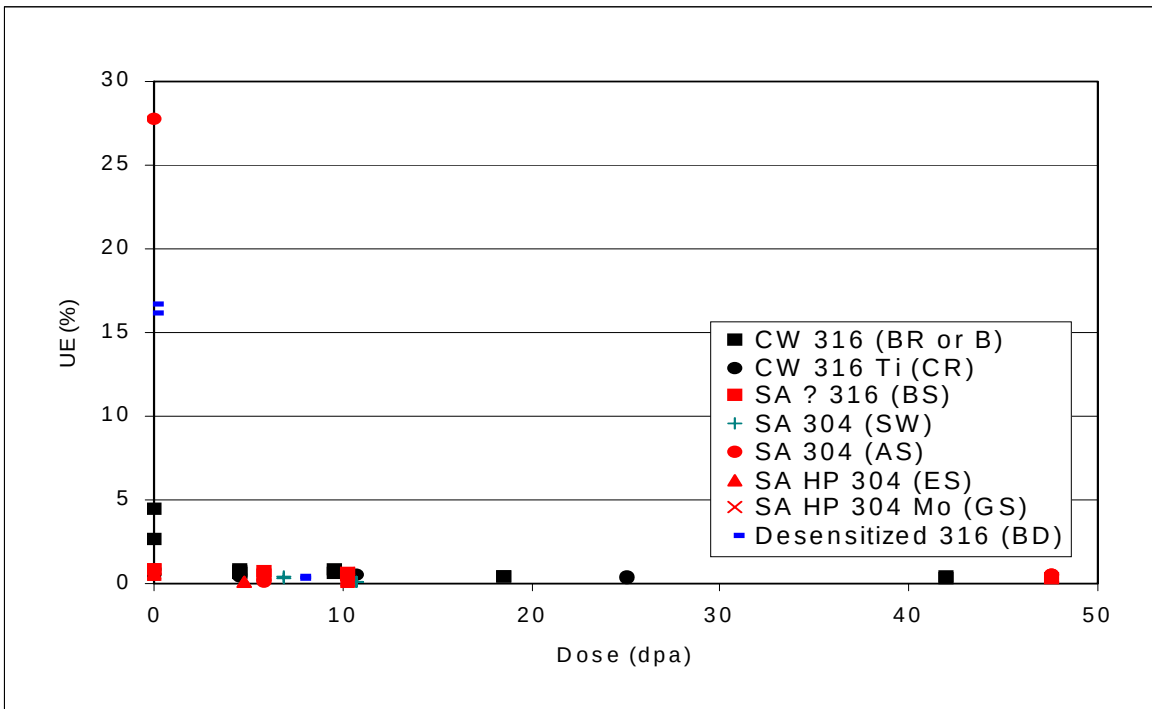


Figure 7-3
Uniform Elongation (at 330°C) as a Function of Damage Dose

Tensile Tests Results

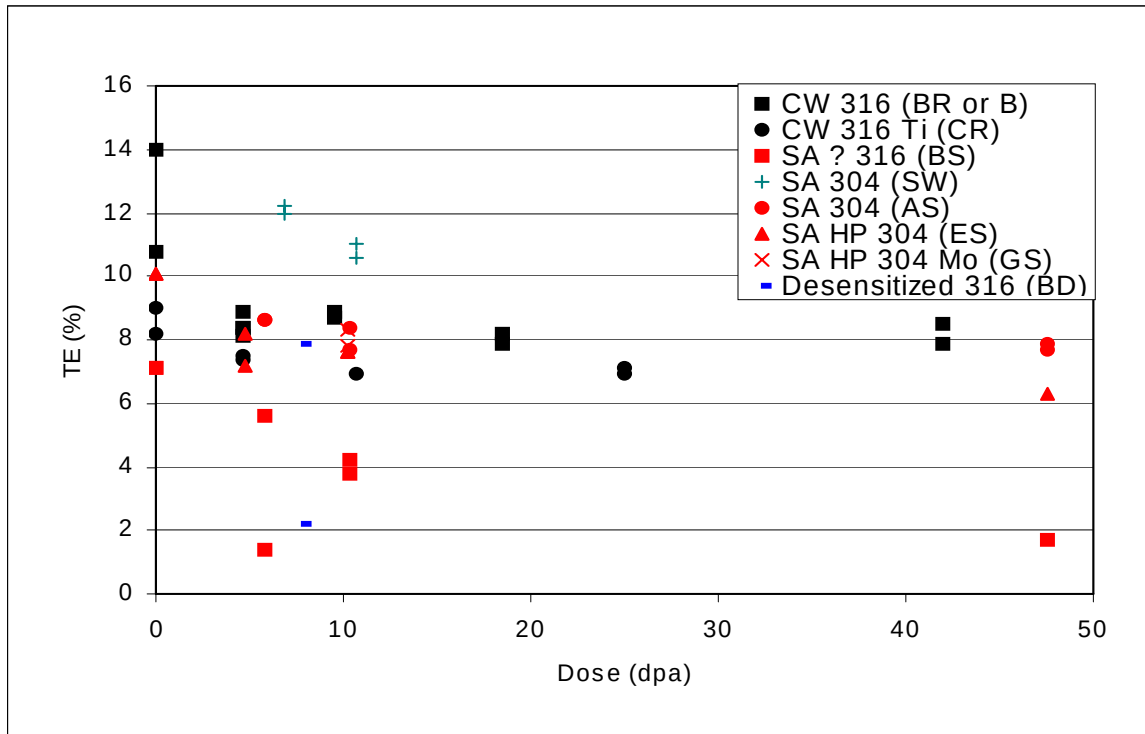


Figure 7-4

Total Elongation (at 330°C) as a Function of Damage Dose

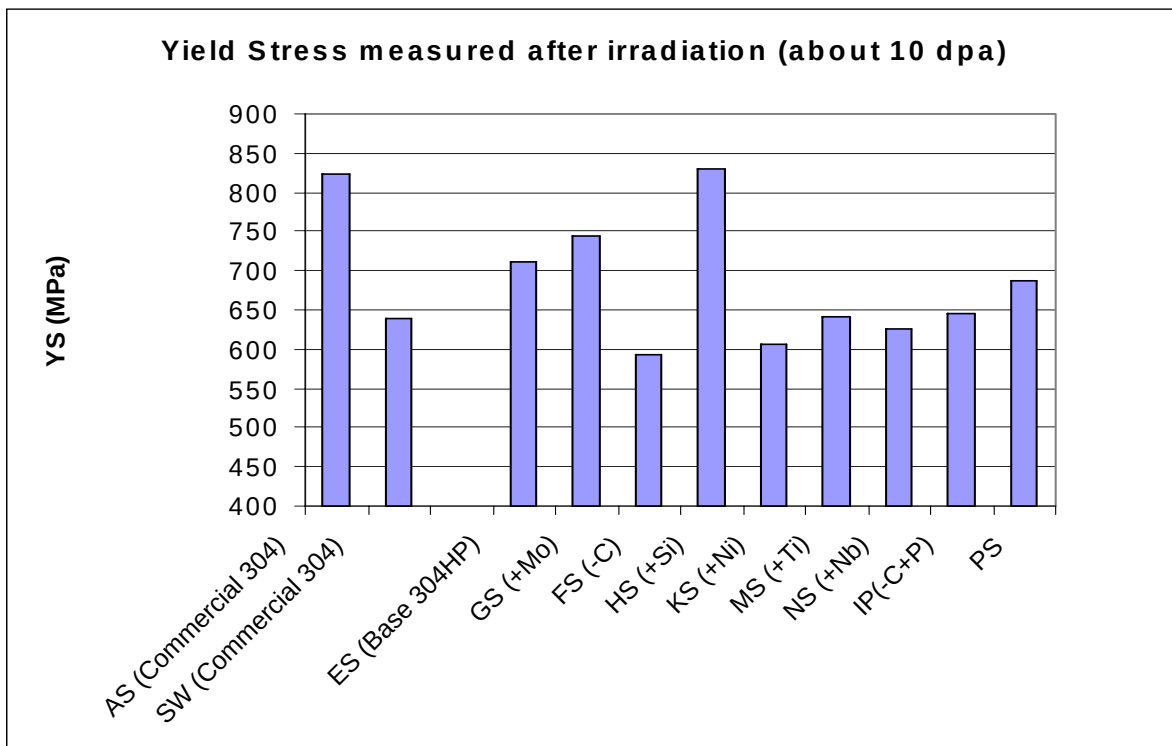


Figure 7-5

Yield Stress (at 330°C) at 10 dpa for the Different Tailored Materials

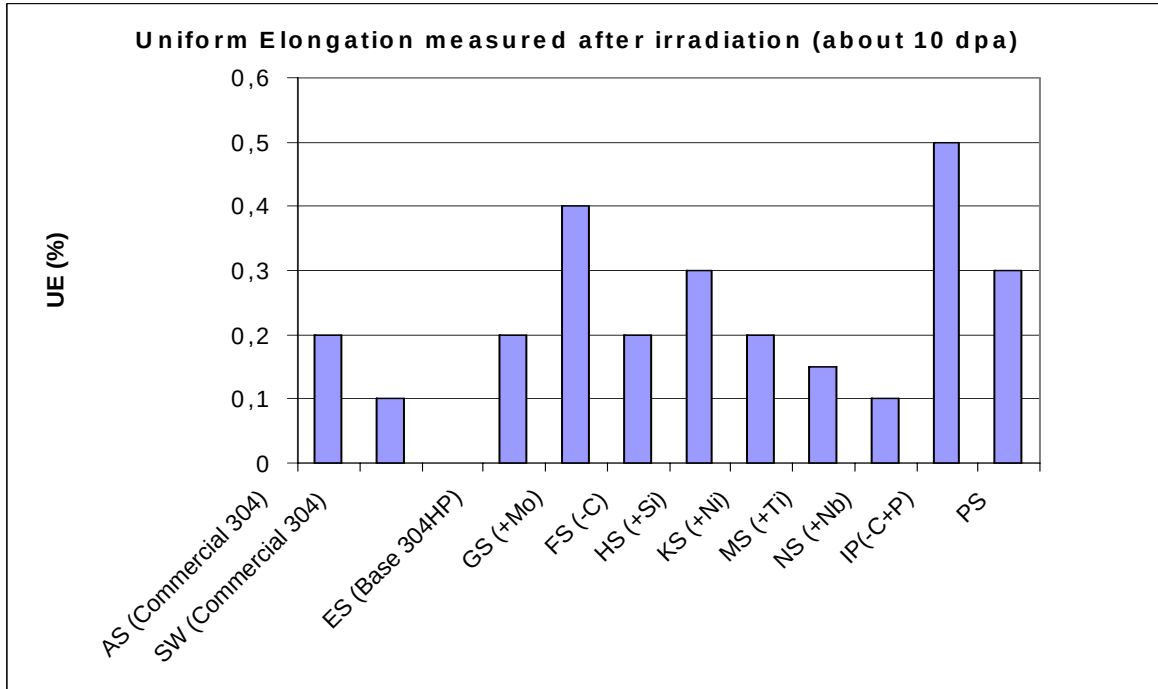


Figure 7-6
Uniform Elongation (at 330°C) at 10 dpa for the Different Tailored Materials

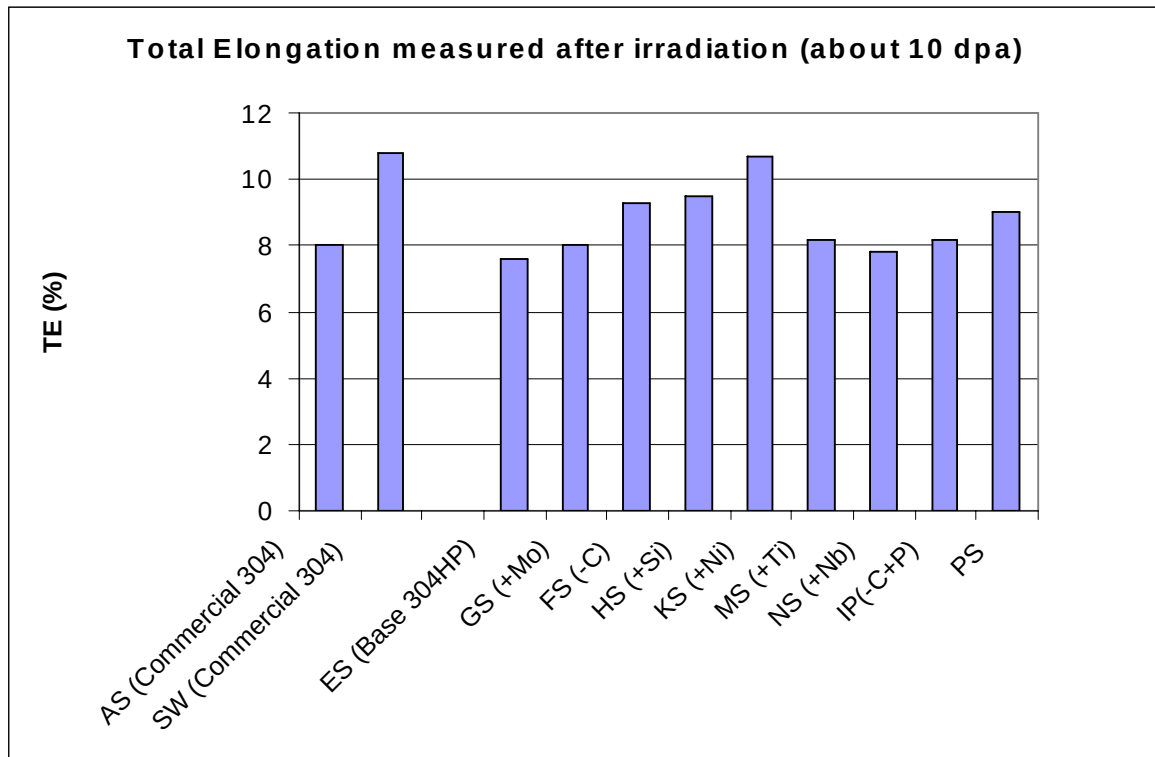


Figure 7-7
Total Elongation (at 330°C) at 10 dpa for the Different Tailored Materials

Tensile Tests Results

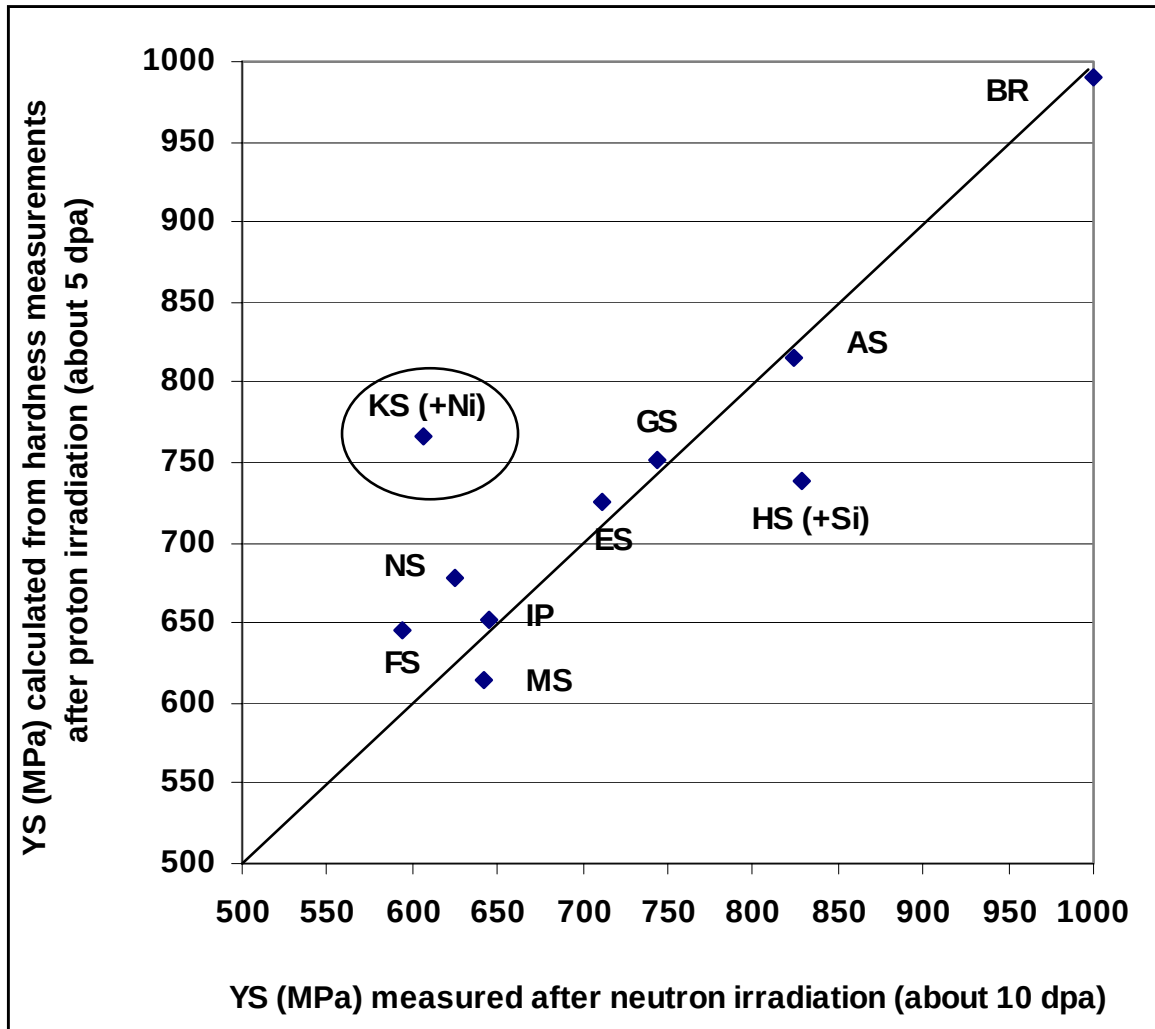


Figure 7-8

Comparison of the Yield Strength Data for these Neutron Irradiations to the Proton Irradiation Hardness Data for the Same Alloys Using Conversion Formula to go from YS to Hardness Developed in the CIR Program

Table 7-1
Results of the Tensile Tests (1)

Material	Specimen	Exp.	Dose (dpa)	Temp. (°C)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)	Reduction (%)
BR or B (CW 316)	B46		0	330	486	614	2.7	10.8	–
	B47		0	330	488	604	4.5	14.0	–
	Mean		0	330	487	609	3.6	12.4	–
	B130	Boris 6	4.8	330	867	893	0.7	8.9	54
	B131	Boris 6	4.8	330	866	891	0.7	9.2	57
	BR13	Boris 6	4.8	330	850	872	0.6	8.4	59
	BR14	Boris 6	4.8	330	859	882	0.6	8.1	54
	Mean		4.8	330	860	884	0.6	8.6	56
	B8	Boris 1	9.6	330	985	1040	0.8	8.9	–
	B2	Boris 1	9.6	330	1013	1052	0.6	8.7	–
	Mean		9.6	330	999	1046	0.7	8.8	–
	B90	Boris 3	17.7	330	944	961	0.4	7.3	58
	B91	Boris 3	17.7	330	949	962	0.4	7.1	71
	Mean		17.7	330	947	962	0.4	7.2	64
	B85	Boris 3+4	42	330	940	965	0.5	7.7	69
	B86	Boris 3+4	42	330	939	949	0.4	7.1	71
	Mean		42	330	940	957	0.5	7.4	70
BS (SA 316)	BS19		0	330	881	923	0.9	7.1	45
	Mean		0	330	881	923	0.9	7.1	45
	BS11	Boris 6	5.5	330	1061	1087	0.5	1.4	35
	BS12	Boris 6	5.5	330	1050	1091	0.7	5.6	38
	Mean		5.5	330	1055	1089	0.6	3.5	36
	BS14	Boris 6	10.2	330	1083	1115	0.5	4.2	36
	BS15	Boris 6	10.2	330	1090	1122	0.6	3.8	35
	Mean		10.2	330	1086	1118	0.5	4.0	35
AS (SA 304)	BS17	Boris 7	47.5	330	1111	1124	0.3	1.7	–
	AS24		0	330	208	457	27.8	37.4	81
	AS25		0	330	219	464	30.2	40.6	78
	Mean		0	330	213	460	29.0	39.0	79
	AS11	Boris 6	5.5	330	791	791	0.2	8.6	57
	AS12	Boris 6	5.5	330	776	776	0.2	8.2	64
	Mean		5.5	330	783	783	0.2	8.4	60
	AS15	Boris 6	10.2	330	821	824	0.3	8.4	59
	AS16	Boris 6	10.2	330	828	828	0.2	7.7	52
	Mean		10.2	330	824	826	0.2	8.0	55
	AS20	Boris 7	47.5	330	903	909	0.5	7.9	49
	AS21	Boris 7	47.5	330	910	917	0.5	7.7	47
	Mean		47.5	330	906	913	0.5	7.8	48

Tensile Tests Results

Table 7-2
Results of the Tensile Tests (2)

Material	Specimen	Exp.	Dose (dpa)	Temp. (°C)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)	Reduction (%)
CR CW 316Ti	CR20		0	330	757	771	0.5	8.2	54
	CR21		0	330	726	766	0.9	9.0	50
	Mean		0	330	741	768	0.7	8.5	52
	CR11	Boris 6	4.8	330	960	972	0.4	7.4	57
	CR12	Boris 6	4.8	330	937	952	0.5	6.8	55
	Mean		4.8	330	948	962	0.4	7.1	56
	CR22	Boris 7	10.7	330	1018	1039	0.5	6.9	49
	Mean		10.7	330	1018	1039	0.5	6.9	49
	CR15	Boris 6	25.0	330	1082	1094	0.4	7.1	53
	CR16	Boris 6	25.0	330	1045	1052	0.3	6.9	59
	Mean		25.0	330	1063	1073	0.3	7.0	56
ES HP SA 304	ES19		0	330	534	550	0.5	10.1	40
	ES20		0	330	527	544	0.6	10.1	54
	Mean		0	330	530	547	0.5	10.1	47
	ES15	Boris 6	4.8	330	712	712	0.2	7.9	67
	ES17	Boris 6	4.8	330	713	713	0.1	7.2	73
	Mean		4.8	330	712	712	0.1	7.5	70
	ES11	Boris 6	10.2	330	719	719	0.1	7.6	61
	ES12	Boris 6	10.2	330	704	709	0.3	7.6	61
	Mean		10.2	330	711	714	0.2	7.6	61
	ES18	Boris 7	47.5	330	678	691	0.4	6.3	43
GS HP SA 304 Mo	GS15	Boris 7-1	7.8	330	735	736	0.2	8.9	71
	GS11	Boris 6	10.2	330	754	755	0.2	7.8	57
	GS12	Boris 6	10.2	330	735	749	0.6	8.3	63
	Mean		10.2	330	744	752	0.4	8.0	60
BD	BD13		0	330	260	510	16.7	26.0	70
	BD14		0	330	288	512	16.2	24.8	77
	Mean		0	330	274	511	16.4	25.4	73
	BD11	Boris 7-1	7.8	330	963	967	0.3	7.9	56
	BD12	Boris 7-1	7.8	330	853	857	0.4	2.2	38
	Mean		7.8	330	908	912	0.3	5.0	47
FS	FS11	Boris 7-1	9.1	330	600	600	0.2	9.4	49
	FS12	Boris 7-1	9.1	330	588	588	0.2	9.3	53
	Mean		9.1	330	594	594	0.2	9.3	51
HS	HS11	Boris 7-1	7.8	330	834	836	0.3	9.2	38
	HS12	Boris 7-1	7.8	330	824	827	0.3	9.8	28
	Mean		7.8	330	829	831	0.3	9.5	32
KS	KS11	Boris 7-1	9.6	330	632	632	0.1	9.9	72
	KS12	Boris 7-1	9.6	330	580	581	0.3	11.5	69
	Mean		9.6	330	606	606	0.2	10.7	70

Table 7-3
Results of the Tensile Tests (3)

Material	Specimen	Exp.	Dose (dpa)	Temp. (°C)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)	Reduction (%)
MS	MS11	Boris 7-3	10.7	330	654	654	0.1	7.6	61
	MS12	Boris 7-3	10.7	330	630	630	0.2	8.9	65
	Mean		10.7	330	642	642	0.15	8.2	63
NS	NS11	Boris 7-3	10.7	330	613	613	0.1	7.8	41
	NS12	Boris 7-3	10.7	330	638	638	0.1	7.8	70
	Mean		10.7	330	625	625	0.1	7.8	55
PS	PS11	Boris 7-1	8	330	698	703	0.4	10.4	55
	PS12	Boris 7-1	8	330	678	680	0.3	7.5	52
	Mean		8	330	688	691	0.3	9.0	53
IP	IP11	Boris 7-3	11.3	330	661	665	0.3	7.1	56
	IP12	Boris 7-3	11.0	330	630	660	0.7	9.4	57
	Mean		11.3	330	645	645	0.5	8.2	56
SW	SW34	Boris 7-2	6.9	330	618	629	0.4	12.2	62
	SW35	Boris 7-2	6.9	330	628	633	0.3	12.0	60
	Mean		6.9	330	623	631	0.35	12.1	61
	SW30	Boris 7-3	10.7	330	641	641	0.1	10.6	70
	SW31	Boris 7-3	10.7	330	635	635	0.1	11.0	67
	Mean		10.7	330	638	638	0.1	10.8	68

Table 7-4
Comparison of Tensile Tests Results After 10dpa Irradiation on Same Material Previously Solution Annealed in the Frame of CIR Program and in an other Frame (EDF-CEA)

	Specimen	Exp.	Dose	Temp.	YS	UTS	UE	TE
SA 316-1 (CIR)	BS14	Boris 6	10.2	330	1083	1115	0.5	4.2
SA 316-1 (CIR)	BS15	Boris 6	10.2	330	1090	1122	0.6	3.8
SA 316-1 (EDF-CEA)	C16	Boris 6	10.2	330	796	854	0.9	8.9
SA 316-1 (EDF-CEA)	C17	Boris 6	10.2	330	823	857	0.8	9.2

8

CONCLUSIONS

The Boris experiment consisted of irradiation of test specimens in the Bor-60 fast breeder reactor of the Research Institute for Atomic Reactors (RIAR, Russia), at a temperature close to 320°C. The Boris experiment was made of irradiation cycles providing about 20 dpa each. The irradiation Boris 7 finished on May 25, 2004. The specimens have received damage doses between 5 and 47,5 dpa. The temperature of the specimens was ~320°C.

This report gives a brief description of the CIR materials involved in the Boris 6 and 7 experiments: five materials representative of the materials for the core internals (solution annealed 304L, solution annealed 316, cold worked 316 and cold worked 316 titanium stabilized) and several tailored materials (high purity 304L with additions).

The results of the tensile tests performed after irradiation on these materials are also given. The engineering tensile curves are typical of austenitic stainless steels irradiated at low temperature: very high yield strength, very little strain hardening and early necking, but with reductions of area which are not strongly affected by irradiation and remains very high.

The tensile tests results of the different materials have been compared to investigate the influence of each solute addition. Results are consistent with the results obtained after proton irradiations.

8.1 References

1. "Research reactors of RIAR and their experimental possibilities". Report by the RIAR state scientific research centre, Dimitrovgrad, Russia, 1995.
2. Markina N., Ryazanov D., Tellin A., Lichadeev V., Pavlov V., Tsikanov V., Ait Abderrahim H., Vanmechelen P., Paardekooper A., Voorbraak W., Nolthenius H., Seren T., Stephan I. and Zaritsky S., "International neutron dosimetry characterisation at Korpus facility: interlaboratory dosimetry calibration results". ANS Protection and Shielding Conference, Nashville, Tennessee, USA, April 98.
3. The use of proton irradiation to determine IASCC mechanisms in Light Water Reactor: Solute addition alloys. EPRI report 1007440.
4. Pokor C., Brechet Y., Dubuisson P., Massoud J-P., Averty X. "Irradiation damage in 304 and 316 steels: experimental investigation and modeling. Part II: Irradiation induced hardening." JNM 326 (2004) 30-37.
5. The use of proton irradiation to determine IASCC mechanisms in Light Water Reactor: solute addition alloys. August 2003. EPRI report 1007440.

A

SPECIMENS DESIGN

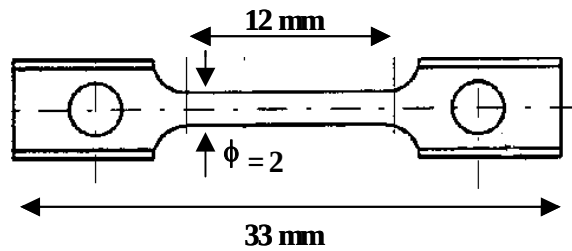
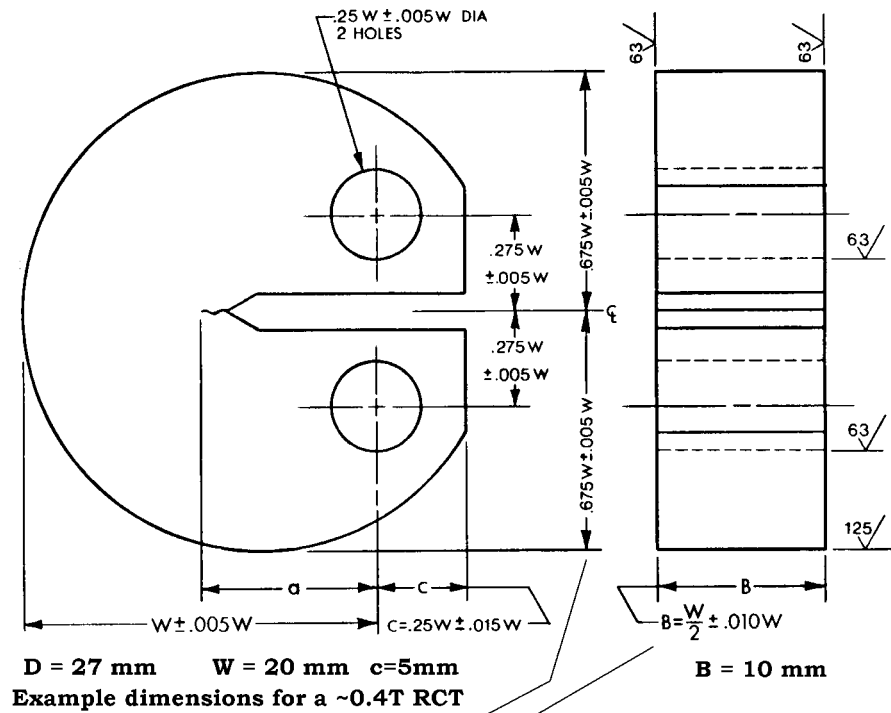


Figure A-1
Cylindrical Tensile Test Specimens Irradiated in the Different Reactor



Note: $B = 8$ mm for heats AS, BS, BR and CR.
 $B = 6$ mm for heats ES and GS.

PL Andresen June 6, 2000

Figure A-2
Drawing of RCT Specimens Irradiated in Boris for the CIR-II Program

Specimens Design

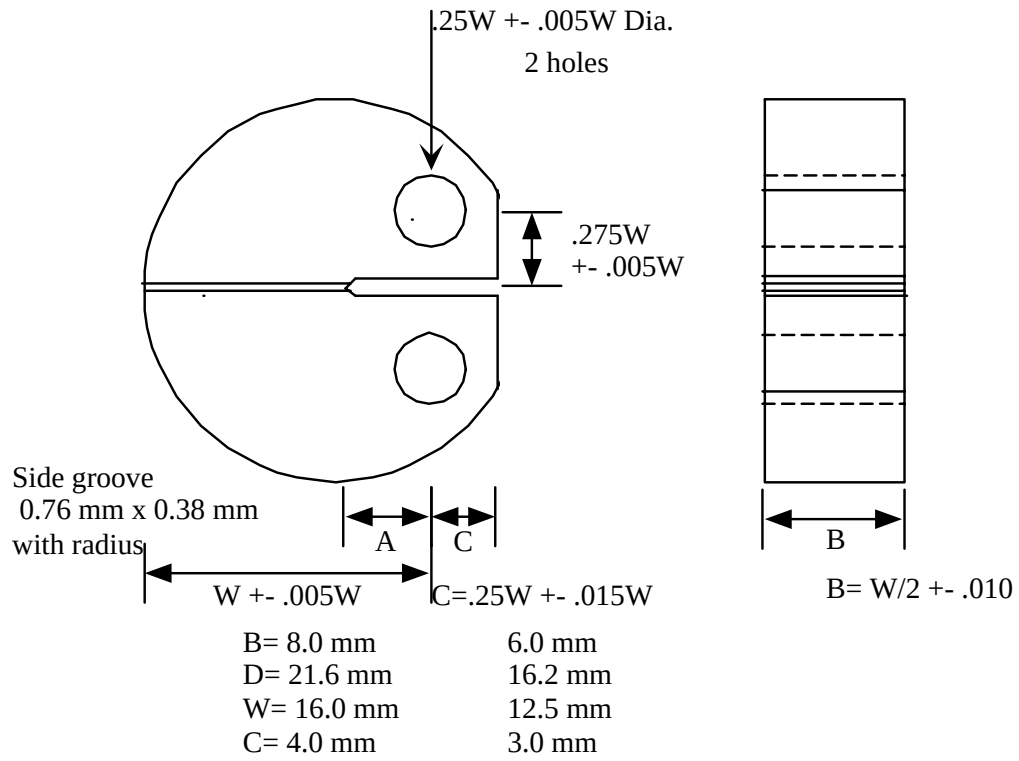


Figure A-3
CT Sample Design

1. DIMENSIONS IN INCHES.
2. GAUGE LENGTH SHALL BE PARALLEL. SPECIMEN SHALL BE PARALLEL TO ROLLING DIRECTION SHOWN ON SUPPLIED ALLOY SHEET.
3. HEAT I.D. NUMBER (YY) IS GIVEN ON SUPPLIED ALLOY PLATES OR SHEETS. SPECIMEN SERIAL NUMBER (ZZ) AS 01, 02, 03, etc.
4. CLEAN MACHINED SPECIMENS WITH ACETONE FOLLOWED BY ALCOHOL IN ULTRASONIC BATH.

B

TEM CAPSULES CONTENT

Table B-1
CIR 5A Capsule

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
1	GE Heat A	AR50	27		AS52	53		ES54	79		IS56
2		AR51	28		AS53	54		ES55	80	GE Heat M Soln Ann.	MS50
3		AR52	29		AS54	55		ES56	81		MS51
4		AR53	30		AS55	56		ES57	82		MS52
5		AR54	31		AS56	57	GE Heat L Soln Ann.	LS50	83		MS53
6		AR55	32		AS57	58		LS51	84		MS54
7		AR56	33	GE Heat B Soln Ann.	BS50	59		LS52	85		MS55
8		AR57	34		BS51	60		LS53	86		MS56
9	GE Heat B	BR50	35		BS52	61		LS54	87		MS57
10		BR51	36		BS53	62		LS55	88	NERI 316L	OL50
11		BR52	37		BS54	63		LS56	89		OL51
12		BR53	38		BS55	64		LS57	90		OL52
13		BR54	39		BS56	65	GE Heat H Soln Ann.	HS50	91		OL53
14		BR55	40		BS57	66		HS51	92	18Cr	6R
15		BR56	41	GE Heat C Soln Ann.	CS50	67		HS52	93	15Cr	6N
16		BR57	42		CS51	68		HS53	94	12Cr	6A04
17	GE Heat C	CR50	43		CS52	69		HS54	95	F82H-II	FH00
18		CR51	44		CS53	70		HS55	96		FH01
19		CR52	45		CS54	71		HS56	97	12Cr	6A04
20		CR53	46		CS55	72		HS57	98	15Cr	6N
21		CR54	47		CS56	73	GE Heat I Soln Ann.	IS50	99	18Cr	6R
22		CR55	48		CS57	74		IS51	100	30Ni-15Cr	330P
23		CR56	49	GE Heat E Soln Ann.	ES50	75		IS52	101	20Ni-15Cr	300J
24		CR57	50		ES51	76		IS53	102		300T
25	GE Heat A Soln Ann.	AS50	51		ES52	77		IS54	103	9Cr-1 Mo	PT
26		AS51	52		ES53	78		IS55	104		PT

TEM Capsules Content

Table B-1
CIR 5A Capsule (Continued)

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
105	7.5 Cr-20Ni	2V05	131			157			813		
106		2V0J	132			158			184		
107	12Cr-20Ni	2X01	133			159			185		
108		2X0T	134			160			186		
109	15Cr-35Ni	350A	135			161			187		
110		350H	136			162			188		
111	D68C11	BLANK	137			163			189		
112		BLANK	138			164			190		
113		BLANK	139			165			191		

Table B-2
CIR 5B Capsule

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
1	GE Heat F Soln Ann.	FS50	27		IP52	53		SH52	79	GE Heat B Lt Sens.	BL50
2		FS51	28		IP53	54		SH53	80		BL51
3		FS52	29		IP54	55	GE Heat B Desens.	BD50	81		BL52
4		FS53	30		IP55	56		BD51	82		BL53
5		FS54	31		IP56	57		BD52	83		BL54
6		FS55	32		IP57	58		BD53	84		BL55
7		FS56	33	GE Heat K Soln Ann	KS50	59		BD54	85	GA3X	9A01
8		FS57	34		KS51	60		BD55	86		9A02
9	GE Heat G Soln Ann.	GS50	35		KS52	61	ABB Heat K	UK50	87		9A03
10		GS51	36		KS53	62		UK51	88		9A04
11		GS52	37		KS54	63		UK52	89	F82H	9F01
12		GS53	38		KS55	64		UK53	90		9F02
13		GS54	39		KS56	65	ABB Heat C	TC50	91		9F03
14		GS55	40		KS57	66		TC51	92		9F04
15		GS56	41	GE Heat B HT Sens.	BT50	67	ABB Heat P	VP50	93	3Cr	65
16		GS57	42		BT51	68		VP51	94	6Cr	6607
17	GE Heat N Soln Ann.	NS50	43		BT52	69		VP52	95	9Cr	67
18		NS51	44		BT53	70		VP53	96	JLF-1	JL00
19		NS52	45		BT54	71	NRC 316 LN	WN50	97	JLF-1	JL01
20		NS53	46		BT55	72		WN51	98	3Cr	65
21		NS54	47	NERI 316L + Pt.	PP50	73		WN52	99	6Cr	66
22		NS55	48		PP51	74		WN53	100	9Cr	67
23		NS56	49		PP52	75	BES 304 P	XP50	101	9Cr	67
24		NS57	50		PP53	76		XP51	102	ODS 14Cr	HN
25	GE Heat I Phos. Seg.	IP50	51	NERI 316L +Hf.	SH50	77		XP52	103		HN
26		IP51	52		SH51	78		XP53	104	ODS 9Cr	H0

TEM Capsules Content

Table B-2
CIR 5B Capsule (Continued)

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
105	ODS 9Cr	H0	131			157			813		
106	MA957	RM	132			158			184		
107		RM	133			159			185		
108	HT-9	9E55	134			160			186		
109		9E56	135			161			187		
110	ODS MA957	6Z	136			162			188		
111		6Z	137			163			189		
112	12Ni- 15Cr	2T0H	138			164			190		
113		2T0V	139			165			191		
114	15Ni- 15Cr	7A0V	140			166			192		
115		7A0V	141			167			193		
116	25Ni- 15Cr	320T	142			168			194		
117		32OR	143			169			195		
118	30Ni- 15Cr	330T	144			170			196		

Table B-3
CIR 10A Capsule

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
1	GE Heat A	AR58	27		AS60	53		ES62	79		IS63
2		AR59	28		AS61	54		ES63	80	GE Heat M Soln Ann.	MS58
3		AR60	29		AS62	55		ES64	81		MS59
4		AR61	30		AS63	56		ES65	82		MS60
5		AR62	31		AS64	57	GE Heat L Soln Ann.	LS58	83		MS61
6		AR63	32		AS65	58		LS59	84		MS62
7		AR64	33	GE Heat B Soln Ann.	BS58	59		LS60	85		MS63
8		AR65	34		BS59	60		LS61	86		MS64
9	GE Heat B	BR58	35		BS60	61		LS62	87		MS65
10		BR59	36		BS61	62		LS63	88	NERI 316L	OL54
11		BR60	37		BS62	63		LS64	89		OL55
12		BR61	38		BS63	64		LS65	90		OL56
13		BR62	39		BS64	65	GE Heat H Soln Ann.	HS58	91		OL57
14		BR63	40		BS65	66		HS59	92	18Cr	6R0U
15		BR64	41	GE Heat C Soln Ann.	CS58	67		HS60	93	15Cr	6N0B
16		BR65	42		CS59	68		HS61	94	12Cr	6A0E
17	GE Heat C	CR58	43		CS60	69		HS62	95	F82H-II	FH02
18		CR59	44		CS61	70		HS63	96		FH03
19		CR60	45		CS62	71		HS64	97	12Cr	6A0E
20		CR61	46		CS63	72		HS65	98	15Cr	6N0B
21		CR62	47		CS64	73	GE Heat I Soln Ann.	IS57	99	18Cr	6R0U
22		CR63	48		CS65	74		IS58	100	30Ni-15Cr	3306
23		CR64	49	GE Heat E Soln Ann.	ES58	75		IS59	101	20Ni-15Cr	3007
24		CR65	50		ES60	76		IS60	102		3005
25	GE Heat A Soln Ann.	AS58	51		ES60	77		IS61	103	9Cr-1Mo	PT
26		AS59	52		ES61	78		IS62	104		PT

TEM Capsules Content

Table B-3
CIR 10A Capsule (Continued)

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
105	7.5 Cr-20Ni	2V07	131			157			813		
106		2V0K	132			158			184		
107	12 Cr-20Ni	2X0U	133			159			185		
108		2X0F	134			160			186		
109	15 Cr-35Ni	3501	135			161			187		
110		3506	136			162			188		
111	D68C11	BLANK	137			163			189		
112		BLANK	138			164			190		
113		BLANK	139			165			191		

Table B-4
CIR 10B Capsule

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
1	GE Heat F Soln Ann.	FS58	27		IP60	53		SH56	79	GE Heat B Lt Sens.	BL56
2		FS59	28		IP61	54		SH57	80		BL57
3		FS60	29		IP62	55	GE Heat B Desens.	BD56	81		BL58
4		FS61	30		IP63	56		BD57	82		BL59
5		FS62	31		IP64	57		BD58	83		BL60
6		FS63	32		IP65	58		BD59	84		BL61
7		FS64	33	GE Heat K Soln Ann	KS58	59		BD60	85	GA3X	9A05
8		FS65	34		KS59	60		BD61	86		9A06
9	GE Heat G Soln Ann.	GS58	35		KS60	61	ABB Heat K	UK54	87		9A07
10		GS59	36		KS61	62		UK55	88		9A08
11		GS60	37		KS62	63		UK56	89	F82H	9F05
12		GS61	38		KS63	64		UK57	90		9F06
13		GS62	39		KS64	65	ABB Heat C	TC52	91		9F07
14		GS63	40		KS65	66		TC53	92		9F08
15		GS64	41	GE Heat B HT Sens.	BT56	67	ABB Heat P	VP54	93	3Cr	6505
16		GS65	42		BT57	68		VP55	94	6Cr	660K
17	GE Heat N Soln Ann.	NS58	43		BT58	69		VP56	95	9Cr	6701
18		NS59	44		BT59	70		VP57	96	JLF-1	JL02
19		NS60	45		BT60	71	NRC 316 LN	WN54	97	JLF-1	JL03
20		NS61	46		BT61	72		WN55	98	3Cr	6504
21		NS62	47	NERI 316L + Pt.	PP54	73		WN56	99	6Cr	66
22		NS63	48		PP55	74		WN57	100	9Cr	670T
23		NS64	49		PP56	75	BES 304 P	XP54	101	9Cr	67
24		NS65	50		PP57	76		XP55	102	ODS 14Cr	HN
25	GE Heat I Phos. Seg.	IP58	51	NERI 316L +Hf.	SH54	77		XP56	103		HN
26		IP59	52		SH55	78		XP57	104	ODS 9Cr	H0

TEM Capsules Content

Table B-4
CIR 10B Capsule (Continued)

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
105	ODS 9Cr	H0	131			157			813		
106	MA957	RM	132			158			184		
107		RM	133			159			185		
108	HT-9	9E6U	134			160			186		
109		9E6B	135			161			187		
110	ODS MA957	6Z	136			162			188		
111		6Z	137			163			189		
112	12Ni- 15Cr	2T0C	138			164			190		
113		2T0U	139			165			191		
114	15Ni- 15Cr	7A0U	140			166			192		
115		7A0U	141			167			193		
116	25Ni- 15Cr	320C	142			168			194		
117		3206	143			169			195		
118	30Ni- 15Cr	330U	144			170			196		

Table B-5
CIR 20A Capsule

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
1	GE Heat A	AR66	27		AS68	53		ES70	79	GE Heat M Soln Ann.	MS66
2		AR67	28		AS69	54		ES71	80		MS67
3		AR68	29		AS70	55		ES72	81		MS68
4		AR69	30		AS71	56		ES73	82		MS69
5		AR70	31		AS72	57	GE Heat L Soln Ann.	LS66	83		MS70
6		AR71	32		AS73	58		LS67	84		MS71
7		AR72	33	GE Heat B Soln Ann.	BS66	59		LS68	85		MS72
8		AR73	34		BS67	60		LS69	86		MS73
9	GE Heat B	BR66	35		BS68	61		LS70	87	NERI 316L	OL58
10		BR67	36		BS69	62		LS71	88		OL59
11		BR68	37		BS70	63		LS72	89		OL60
12		BR69	38		BS71	64		LS73	90		OL61
13		BR70	39		BS72	65	GE Heat H Soln Ann.	HS66	91	18Cr	6R0E
14		BR71	40		BS73	66		HS67	92	15Cr	6N0R
15		BR72	41	GE Heat C Soln Ann.	CS66	67		HS68	93	12Cr	6A0F
16		BR73	42		CS67	68		HS69	94	F82H-II	FH04
17	GE Heat C	CR66	43		CS68	69		HS70	95		FH05
18		CR67	44		CS69	70		HS71	96	12Cr	6A0F
19		CR68	45		CS70	71		HS72	97	15Cr	6NR0
20		CR69	46		CS71	72		HS73	98	18Cr	6R
21		CR70	47		CS72	73	GE Heat I Soln Ann.	IS64	99	30Ni-15Cr	330N
22		CR71	48		CS73	74		IS65	100	20Ni-15Cr	300N
23		CR72	49	GE Heat E Soln Ann.	ES66	75		IS66	101		300R
24		CR73	50		ES67	76		IS67	102	9Cr-1Mo	PT
25	GE Heat A Soln Ann.	AS66	51		ES68	77		IS68	103		PT
26		AS67	52		ES69	78		IS69	104	7.5 Cr-20Ni	2V0V

TEM Capsules Content

Table B-5
CIR 20A Capsule (Continued)

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
105	7.5 Cr- 20Ni	2V0X	131			157			813		
106	12Cr- 20Ni	2X0B	132			158			184		
107		2X0V	133			159			185		
108	15Cr- 35Ni	350J	134			160			186		
109		3503	135			161			187		
110	D68C11	BLANK	136			162			188		
111		BLANK	137			163			189		
112		BLANK	138			164			190		

Table B-6
CIR 20B Capsule

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
1	GE Heat F Soln Ann.	FS66	27		IP68	53		SH60	79	GE Heat B Lt Sens.	BL62
2		FS67	28		IP69	54		SH61	80		BL63
3		FS68	29		IP70	55	GE Heat B Desens.	BD62	81		BL64
4		FS69	30		IP71	56		BD63	82		BL65
5		FS70	31		IP72	57		BD64	83		BL66
6		FS71	32		IP73	58		BD65	84		BL67
7		FS72	33	GE Heat K Soln Ann	KS66	59		BD66	85	GA3X	9A09
8		FS73	34		KS67	60		BD67	86		9A10
9	GE Heat G Soln Ann.	GS66	35		KS68	61	ABB Heat K	UK58	87		9A11
10		GS67	36		KS69	62		UK59	88		9A12
11		GS68	37		KS70	63		UK60	89	F82H	9F09
12		GS69	38		KS71	64		UK61	90		9F10
13		GS70	39		KS72	65	ABB Heat C	TC54	91		9F11
14		GS71	40		KS73	66		TC56	92		9F12
15		GS72	41	GE Heat B HT Sens.	BT62	67	ABB Heat P	VP58	93	3Cr	650R
16		GS73	42		BT63	68		VP59	94	6Cr	660R
17	GE Heat N Soln Ann.	NS66	43		BT64	69		VP60	95	9Cr	670U
18		NS67	44		BT65	70		VP61	96	JLF-1	JL04
19		NS68	45		BT66	71	NRC 316 LN	WN58	97	JLF-1	JL05
20		NS69	46		BT67	72		WN59	98	3Cr	650X
21		NS70	47	NERI 316L + Pt.	PP58	73		WN60	99	6Cr	660V
22		NS71	48		PP59	74		WN61	100	9Cr	670U
23		NS72	49		PP60	75	BES 304 P	XP58	101	9Cr	67
24		NS73	50		PP61	76		XP59	102	ODS 14Cr	HN
25	GE Heat I Phos. Seg.	IP66	51	NERI 316L +Hf.	SH58	77		XP60	103		HN
26		IP67	52		SH59	78		XP61	104	ODS 9Cr	H0

TEM Capsules Content

Table B-6
CIR 20B Capsule (Continued)

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
105	ODS 9Cr	H0	131			157			813		
106	MA957	RM	132			158			184		
107		RM	133			159			185		
108	HT-9	9E	134			160			186		
109		9E	135			161			187		
110	ODS MA957	6Z	136			162			188		
111		6Z	137			163			189		
112	12Ni-15Cr	2T0F	138			164			190		
113		2T0X	139			165			191		
114	15Ni-15Cr	7A0F	140			166			192		
115		7AR0	141			167			193		
116	25Ni-15Cr	320X	142			168			194		
117		320A	143			169			195		
118	30Ni-15Cr	330F	144			170			196		

Table B-7
CIR IIA Capsule

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
1	Heat A	AR75	27	Heat A Soln Ann.	AS76	53	Heat I Phos. Seg.	IP80	79	Heat H Soln Ann.	HS78
2		AR76	28		AS77	54		IP81	80		HS79
3		AR77	29	Heat F Soln Ann.	FS75	55		IP82	81		HS80
4	Heat E Soln Ann	ES75	30		FS76	56		IP83	82		HS81
5		ES76	31		FS77	57	Heat K Soln Ann.	KS75	83		HS82
6		ES77	32		FS78	58		KS76	84	Heat N Soln Ann.	NS75
7	Heat B Desens.	BD75	33		FS79	59		KS77	85		NS76
8		BD76	34		FS80	60		KS78	86		NS77
9		BD77	35		FS81	61		KS79	87		NS78
10		BD78	36		FS82	62		KS80	88		NS79
11	Heat B	BR75	37		FS83	63		KS81	89		NS80
12		BR76	38	Heat G Soln Ann.	GS75	64		KS82	90		NS81
13		BR77	39		GS76	65		KS83	91		NS82
14		BR78	40		GS77	66	Heat L Soln Ann.	LS75	92	NERI 316L +Hf.	SH75
15		BR79	41	Heat M Soln Ann.	MS75	67		LS76	93		SH76
16	Heat B HT Sens.	BT68	42		MS76	68		LS77	94		SH77
17		BT69	43		MS77	69		LS78	95		SH78
18		BT70	44		MS78	70		LS79	96		SH79
19	Heat C Soln Ann	CS75	45		MS79	71		LS80	97		SH80
20		CS76	46		MS80	72		LS81	98		SH81
21		CS77	47		MS81	73		LS82	99		SH82
22		CS78	48	Heat I Phos. Seg.	IP75	74		LS83	100		SH83
23		CS79	49		IP76	75		LS84	101	ABB Heat P	VP75
24		CS80	50		IP77	76	Heat H Soln Ann.	HS75	102		VP76
25		CS81	51		IP78	77		HS76	103		VP77
26	Heat A Soln Ann.	AS75	52		IP79	78		HS77	104		VP78

TEM Capsules Content

Table B-7
CIR IIA Capsule (Continued)

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
105		VP79	131	(BLANK)	NO ID	157			183		
106		VP80	132	(BLANK)	NO ID	158			184		
107		VP81	133	(BLANK)	NO ID	159			185		
108	ABB Heak K	UK75	134			160			186		
109		UK76	135			161			187		
110		UK77	136			162			188		
111		UK78	137			163			189		
112		UK79	138			164			190		
113		74BS	139			165			191		
114		75BS	140			166			192		
115		76BS	141			167			193		
116		77BS	142			168			194		
117	(BLANK)	NO ID	143			169			195		
118	(BLANK)	NO ID	144			170			196		
119	(BLANK)	NO ID	145			171			197		
120	(BLANK)	NO ID	146			172			198		
121	(BLANK)	NO ID	147			173			199		
122	(BLANK)	NO ID	148			174			200		
123	(BLANK)	NO ID	149			175			201		
124	(BLANK)	NO ID	150			176			202		
125	(BLANK)	NO ID	151			177			203		
126	(BLANK)	NO ID	152			178			204		
127	(BLANK)	NO ID	153			179			205		
128	(BLANK)	NO ID	154			180			206		
129	(BLANK)	NO ID	155			181			207		
130	(BLANK)	NO ID	156			182			208		

Table B-8
CIR IIB Capsule

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
1	Heat A	AR78	27	Heat A Soln Ann.	AS79	53	Heat I Phos. Seg	IP90	79	Heat H Soln Ann.	HS88
2		AR79	28		AS80	54		IP91	80		HS89
3		AR80	29	Heat F Soln Ann.	FS84	55		IP92	81		HS90
4	Heat E Soln Ann	ES78	30		FS85	56	Heat K Soln Ann.	KS84	82	Heat N Soln Ann.	NS83
5		ES79	31		FS86	57		KS85	83		NS84
6		ES80	32		FS87	58		KS86	84		NS85
7	Heat B Desens.	BD79	33		FS88	59		KS87	85		NS86
8		BD80	34		FS89	60		KS88	86		NS87
9		BD81	35		FS90	61		KS89	87		NS88
10		BD82	36		FS91	62		KS90	88		NS89
11		BD83	37	Heat G Soln Ann.	GS78	63		KS91	89		NS90
12	Heat B	BR80	38		GS79	64		KS92	90		NS91
13		BR81	39		GS80	65	Heat L Soln Ann.	LS85	91	NERI 316L +Hf.	SH84
14		BR82	40	Heat M Soln Ann.	MS82	66		LS86	92		SH85
15		BR83	41		MS83	67		LS87	93		SH86
16	Heat B HT Sens.	BT71	42		MS84	68		LS88	94		SH87
17		BT72	43		MS85	69		LS89	95		SH88
18		BT73	44		MS86	70		LS90	96		SH89
19	Heat C Soln Ann	CS82	45		MS87	71		LS91	97		SH90
20		CS83	46		MS88	72		LS92	98		SH91
21		CS84	47	Heat I Phos. Seg.	IP84	73		LS93	99		SH92
22		CS85	48		IP85	74	Heat H Soln Ann.	HS83	100	ABB Heat P	VP82
23		CS86	49		IP86	75		HS84	101		VP83
24		CS87	50		IP87	76		HS85	102		VP84
25		CS88	51		IP88	77		HS86	103		VP85
26	Heat A Soln Ann.	AS78	52		IP89	78		HS87	104		VP86

TEM Capsules Content

Table B-8
CIR IIB Capsule (Continued)

	Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code		Alloy or Material	I.D. Code
105	ABB Heat P	VP87	131	(BLANK)	NO ID	157			183		
106		VP88	132			158			184		
107	ABB Heat K	UK80	133			159			185		
108		UK81	134			160			186		
109		UK82	135			161			187		
110		UK83	136			162			188		
111		UK84	137			163			189		
112		78BS	138			164			190		
113		79BS	139			165			191		
114		80BS	140			166			192		
115	(BLANK)	NO ID	141			167			193		
116	(BLANK)	NO ID	142			168			194		
117	(BLANK)	NO ID	143			169			195		
118	(BLANK)	NO ID	144			170			196		
119	(BLANK)	NO ID	145			171			197		
120	(BLANK)	NO ID	146			172			198		
121	(BLANK)	NO ID	147			173			199		
122	(BLANK)	NO ID	148			174			200		
123	(BLANK)	NO ID	149			175			201		
124	(BLANK)	NO ID	150			176			202		
125	(BLANK)	NO ID	151			177			203		
126	(BLANK)	NO ID	152			178			204		
127	(BLANK)	NO ID	153			179			205		
128	(BLANK)	NO ID	154			180			206		
129	(BLANK)	NO ID	155			181			207		
130	(BLANK)	NO ID	156			182			208		

C

STRESS-STRAIN CURVES

Stress-Strain Curves

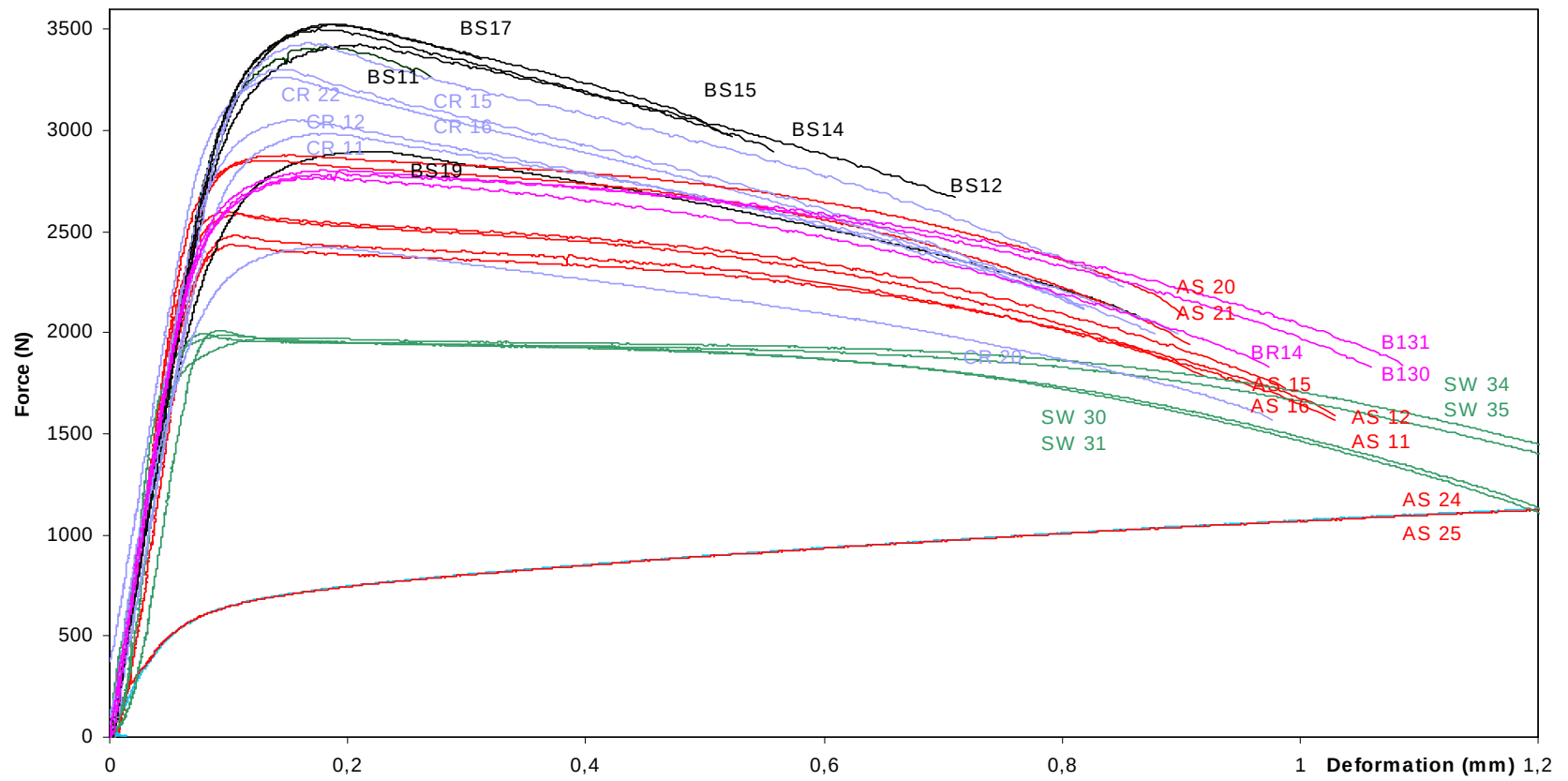


Figure C-1
Tensile Curves. Commercial Grades

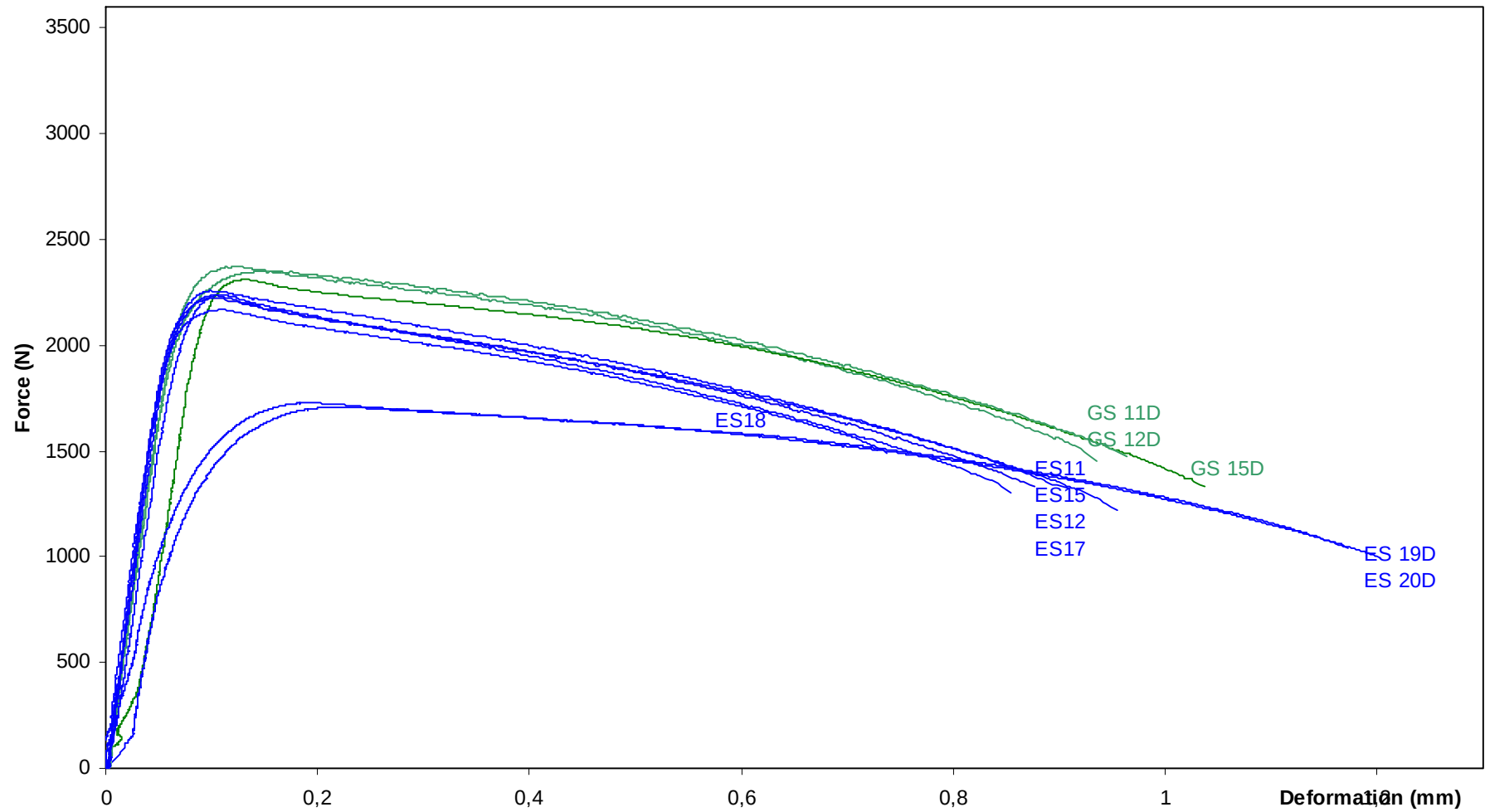


Figure C-2
Tensile Curves. Tailored Alloys

Stress-Strain Curves

Where the specimens did not conform to the EDF drawing (due to the reduced size of the heads and the associated risk that they would rupture at the pin holes if tested in the classical manner), specimen grips were adapted to pull on the specimen shoulders. In this case, extensometry directly on the specimen gage length was precluded and then not used.

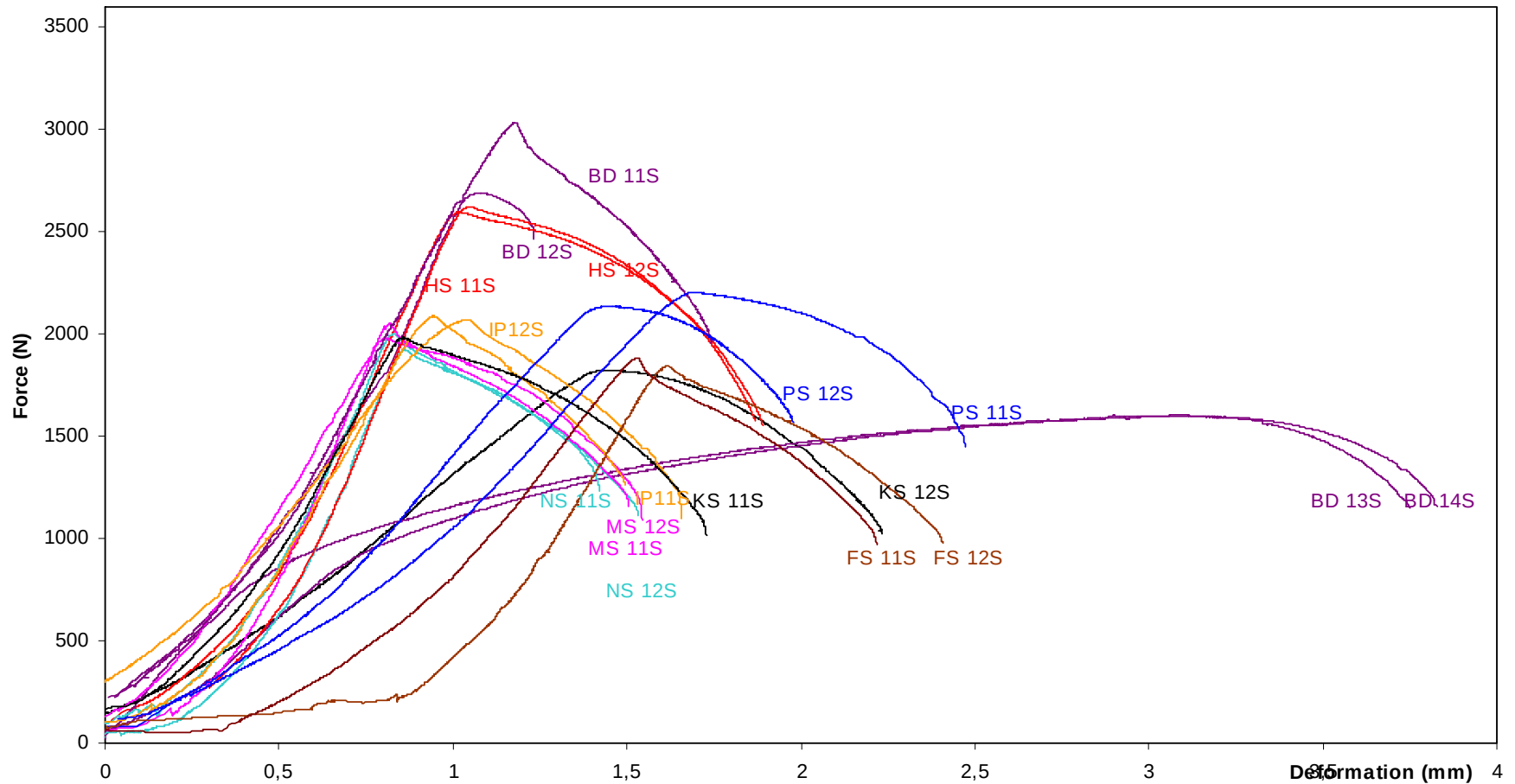


Figure C-3
Tensile Curves. Tailored Alloys

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

© 2005 Electric Power Research Institute (EPRI), Inc. All rights reserved.
Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc.

 Printed on recycled paper in the United States of America

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California, and Charlotte, North Carolina, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together...Shaping the Future of Electricity

Program:
Nuclear Power

1011787

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue, Palo Alto, California 94304-1395 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com