ORNL/TM-2023/3207

Post-Irradiation Examination on Absorber Material Specimens Irradiated in the High Flux Isotope Reactor

A.G. Le Coq
J.W. Werden
K.D. Linton
M. Aumand (Framatome)

Approved for public release. Distribution is unlimited.

August 2024

M3UA-22OR0502012

OAK RIDGE National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2023/3207

Nuclear Science User Facilities

POST-IRRADIATION EXAMINATION ON ABSORBER MATERIAL SPECIMENS IRRADIATED IN THE HIGH FLUX ISOTOPE REACTOR

A.G. Le Coq
J.W. Werden
K.D. Linton
M. Aumand (Framatome)

August 2024

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

HFIR	High Flux Isotope Reactor
LAMDA	Low-Activation Materials Development and Analysis
NSUF	Nuclear Science User Facilities
PIE	post-irradiation examination
SiC	silicon carbide
TM	temperature monitor

ACKNOWLEDGMENTS

This work was funded by the Nuclear User Science Facilities program of the US Department of Energy, Office of Nuclear Energy. The authors would like to acknowledge the contributions of Bob Sitterson for this work on the hot cell jaw gauge, the Irradiated Materials Examination and Testing facility's staff for handling the specimens for these measurements, and Travis Dixon for his input on the measurement procedure.

ABSTRACT

Advanced accident-tolerant absorber material candidates are being investigated as an alternative to current absorber materials used in commercial nuclear reactors. Framatome and Oak Ridge National Laboratory developed a neutron irradiation campaign in the High Flux Isotope Reactor to collect a first set of data on the irradiated behavior of four absorber material candidates: hafnium carbide, hafnium carbide with molybdenum additive, samarium hafnate, and europium hafnate. Two irradiation capsules containing these absorber material specimens were inserted in the reactor and targeted a specimen irradiation temperature around 300°C and irradiation damage levels of 6 dpa and 12 dpa, respectively. The capsules were then disassembled to recover the passive thermometry and the specimens. The passive thermometry was analyzed via dilatometry, and the results show that the average specimen temperature was 305°C and 384°C for the 6 dpa and 12 dpa capsules, respectively. The specimens were dimensionally inspected using an in-cell setup, including a jaw gauge modified for hot cell handling. Length, width, and thickness measurements were recorded for each specimen and compared to the same data recorded pre-irradiation to estimate the irradiation dimensional change of the specimens. The results show no significant dimensional change for the four absorber materials and at the two irradiation damage levels.

1. INTRODUCTION

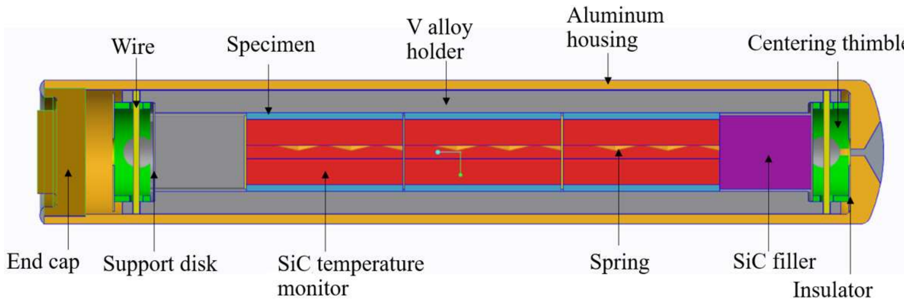
Framatome has been investigating novel absorber materials as an alternative to silver-indium-cadmium (and boron carbide to a lesser extent) currently used in commercial nuclear reactors. The nuclear community has growing interest in advanced accident-tolerant absorber materials that, compared to current absorber silver-indium-cadmium, do not form low-melting eutectics with the fuel cladding and are more stable at higher temperatures, while still having equivalent reactivity worth and control rod drop times.

The materials investigated by Framatome include hafnium carbide, hafnium carbide with molybdenum additive, samarium hafnate, and europium hafnate. To collect the first set of data on the behavior of these novel materials after neutron irradiation, a High Flux Isotope Reactor (HFIR) irradiation campaign was developed in collaboration with Oak Ridge National Laboratory. An irradiation capsule design accommodating small absorber material specimens was designed to target an average specimen temperature of 300°C [1]. Two of these capsules—ABS01 and ABS02—were successfully assembled and inserted into HFIR in peripheral target position 5 for 6 and 12 cycles, respectively [2].

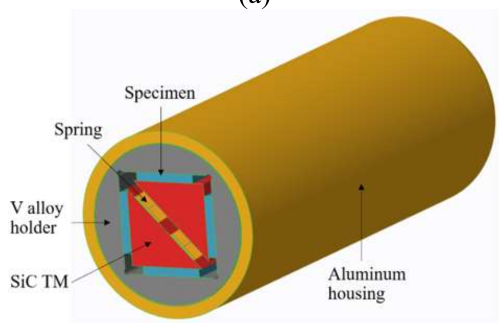
The main purpose of this irradiation is to quantify irradiation-induced swelling of the specimens by comparing specimen dimensions pre- and post-irradiation. This report provides an overview of the experimental capsules. It then presents the capsule disassembly, the dilatometry results confirming the capsule irradiation temperature, and finally the dimensional examination performed post irradiation to quantify the specimens swelling.

2. OVERVIEW OF THE EXPERIMENTAL CAPSULES

The absorber materials capsule design is described in Cetiner et al. [1] and shown in Figure 1. A total of 12 coupon absorber material specimens with dimensions 12 mm × 3.6 mm × 0.50 mm are inserted in the capsule holder. 6 silicon carbide (SiC) passive temperature monitors (TMs) with a triangular cross section are pressed onto the absorber material specimens. Table 1 shows the list of specimens loaded in each of the two absorber material capsules, along with their irradiation conditions. Note that some coupon specimens are made of SiC and act as spacers when absorber material specimens were not available. Capsules ABS01 and ABS02 were irradiated in HFIR for 6 and 12 cycles, respectively, corresponding to a total fast fluence (E > 0.183 MeV) of 1.6×10^{22} and 3.1×10^{22} n/cm^2. APPENDIX A shows the irradiation cycle history for the two capsules.



(a)



(b)

Figure 1. Irradiation capsule design concept: (a) axial section view and (b) radial section view of the capsule [1].

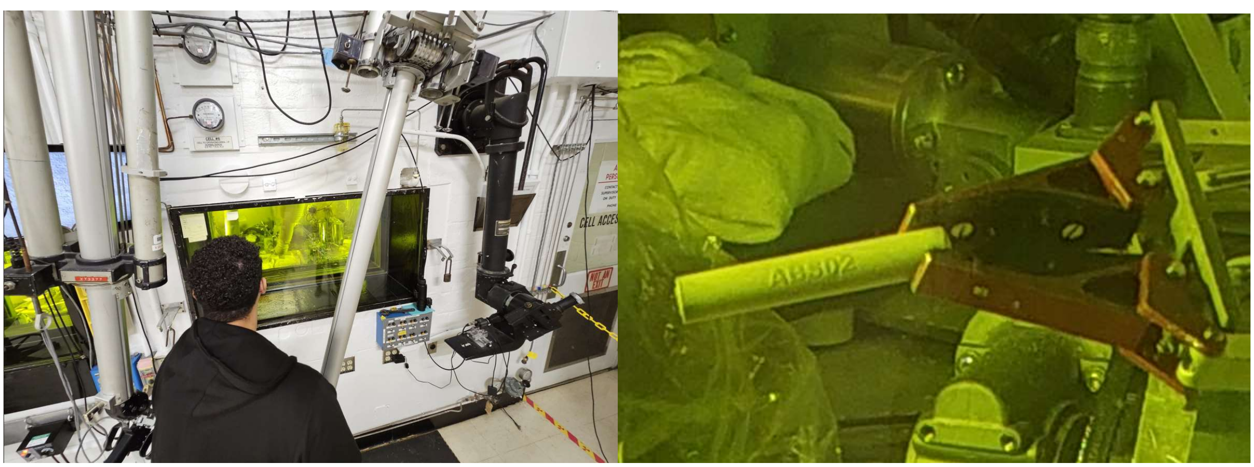
Table 1. Absorber Materials Irradiation Test Matrix

Capsule ID	Irradiation temperature (°C)	Number of cycles	Irradiation cycles	Specimen material	Number of specimens	Specimen ID
ABS01	300	6	From Cycle 488 (June 2020) to Cycle 493 (July 2021)	Hafnium carbide	3	H15 H16 H17
				Hafnium carbide + additive	3	M10 M11 M12
				Samarium hafnate	2	S1 S3
				Europium hafnate	3	E6 E7 E21
				SiC	1	SC-01
ABS02	300	12	From Cycle 488 (June 2020) to Cycle 499 (October 2022)	Hafnium carbide	3	H18 H23 H24
				Hafnium carbide + additive	3	M13 M14 M22
				Samarium hafnate	2	S2 S5
				Europium hafnate	2	E8 E9
				SiC	2	SC-03 SC-04

3. CAPSULE DISASSEMBLY

ABS01 and ABS02 capsules were shipped to the Irradiated Materials Examination and Testing hot-cell facility for disassembly and subsequent post-irradiation examination (PIE). Figure 2 shows images of the capsule disassembly. Each capsule was cut open below the end cap using a low-speed saw. Once the capsule was open, the holder was slid out of the capsule housing and the centering thimbles were removed from the holder. The internal components of the holder were then pushed out to recover the TMs and the absorber material specimens. All TMs were accounted for, intact, and packaged for shipment to the Low-Activation Materials Development and Analysis (LAMDA) laboratory to be analyzed (see Section 4). Each specimen was identified using an in-cell microscope and was individually packaged for subsequent dimensional examination (see Section 5). Figure 3 shows examples of pictures taken in cell for specimen identification, with notches on the europium and samarium hafnate specimens, and engraved ID on the hafnium carbide specimens. Most of the specimens were recovered intact. The following specimens were not recovered intact upon disassembly, and it is unclear whether their damage occurred during assembly, irradiation, or disassembly:

- specimen E6: one corner chipped
- specimen E8: broken, and one main piece was identified
- specimens M13, S5, and E9: each broken into 2 identified pieces



(a) (b)

Figure 2. Capsule disassembly: (a) Operator working at the hot cell window on the disassembly and (b) capsule ABS02 before being cut open.

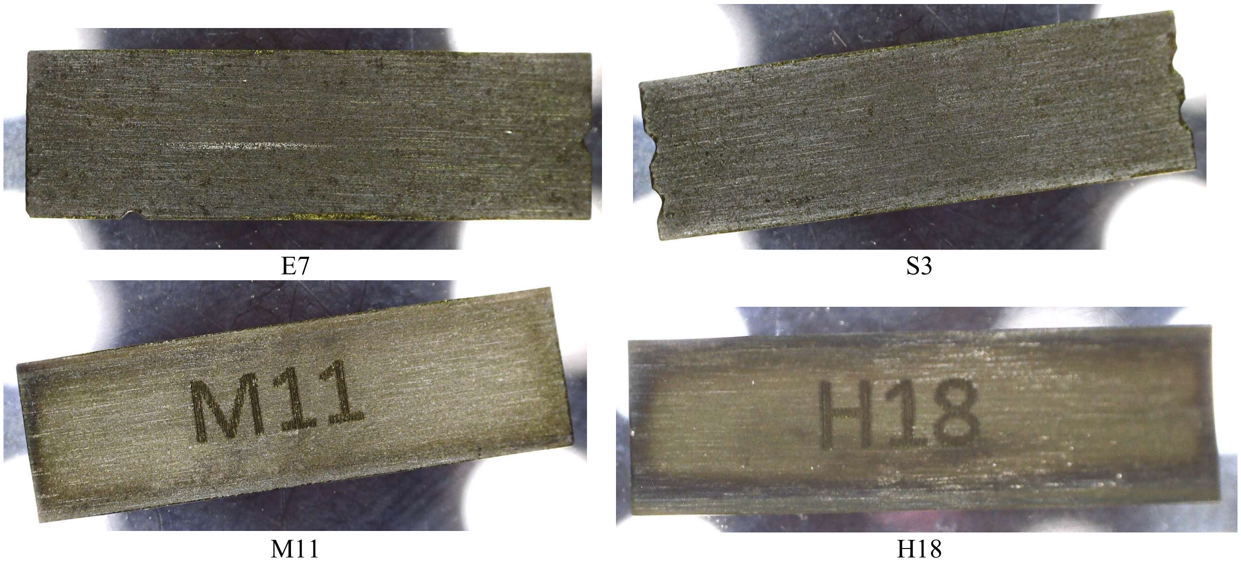


Figure 3. Example of specimens being identified in cell during capsule disassembly.

4. DILATOMETRY RESULTS

Each TM—six per capsule—was analyzed via dilatometry in LAMDA to confirm the experimental irradiation temperature [3][4]. The average TM temperature obtained via dilatometry was then compared with the average predicted TM and specimen temperatures to estimate the specimen average experimental temperature. The results are presented in Table 2 and show an average experimental TM temperature 14% below and 8% above the average predicted TM temperatures for capsules ABS01 and ABS02, respectively.

Table 2. Predicted and Experimental Average Temperatures of the TMs and Absorber Specimens

	ABS01		**ABS02**	
	Average irradiation temperature (°C)			
Component	**Predicted**	**Experimental**	**Predicted**	**Experimental**
TM	390	337 (σ = 19)	374	403 (σ = 51)
All specimens	353	305	356	384
Europium hafnate	370	320	370	399
Samarium hafnate	363	314	359	387
Hafnium carbide	341	294	338	364
Hafnium carbide with additive	342	296	338	365

5. DIMENSIONAL EXAMINATION

Before irradiation, each specimen was dimensionally inspected. The length, width, and thickness of each specimen were measured at various locations, for a total of 3 length measurements, 6 width measurements, and 12 thickness measurements. The details and results of this pre-irradiation inspection are available in Le Coq et al. [2]. The same measurements were taken post irradiation using a similar method to compare the specimen dimensions pre- and post- irradiation and to estimate the swelling of the specimens.

5.1 MEASUREMENT METHOD

5.1.1 Instruments and Equipment

The measurements were performed using a Dorsey J2 horizontal jaw gauge equipped with a set of Dorsey 47950-C contacts and a Mitutoyo Model 543-472B digital indicator (calibrated on April 13, 2023). The jaw gauge was modified to facilitate the work in the hot cell: (1) a foil was added under the stage to prevent any specimen from falling through and under the instrument, and (2) new handles were installed for easier grip and handling with the hot cell manipulator. Figure 4 shows the as-received jaw gauge and the two modifications for in-cell measurements. The final configuration of the jaw gauge for in-cell measurements is shown in Figure 5. Gauge blocks (1, 1.5, 2, and 10 mm) from a Mitutoyo steel gauge block set (code No. 516-101-26) calibrated on June 8, 2023, were used during these measurements (see Figure 6).

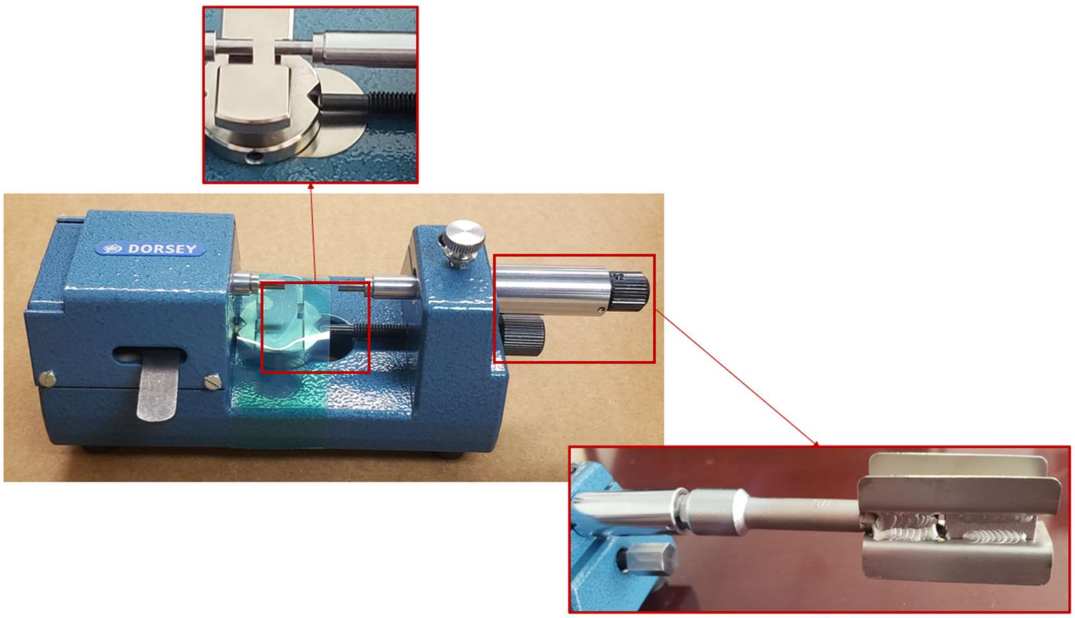


Figure 4. Jaw gauge modifications for hot cell work.

Figure 5. Jaw gauge equipped with digital indicator and modified for hot cell work.

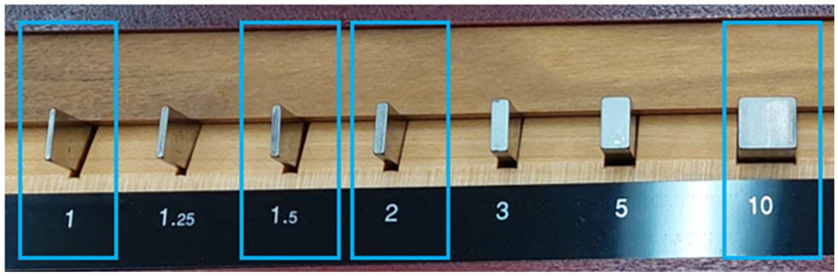


Figure 6. Gauge blocks used during the measurements.

Before in-cell insertion of the jaw gauge, the jaw gauge stage height was adjusted to be as close as possible to the anvils without preventing their movements. The jaw gauge was then inserted in cell and placed on the stage of the copy stand. The measurements setup in shown in Figure 7. The copy stand allows for capturing high-definition pictures of the measurements and provides a visual verification of the measurements.

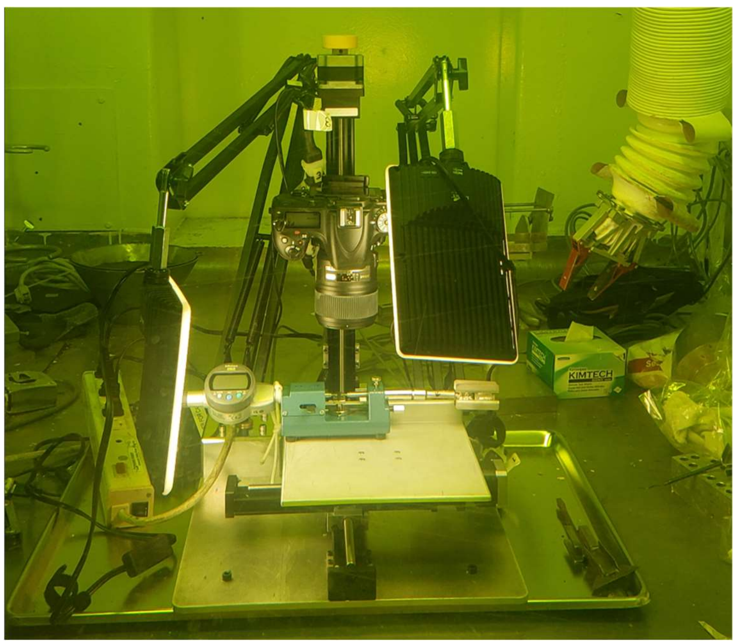
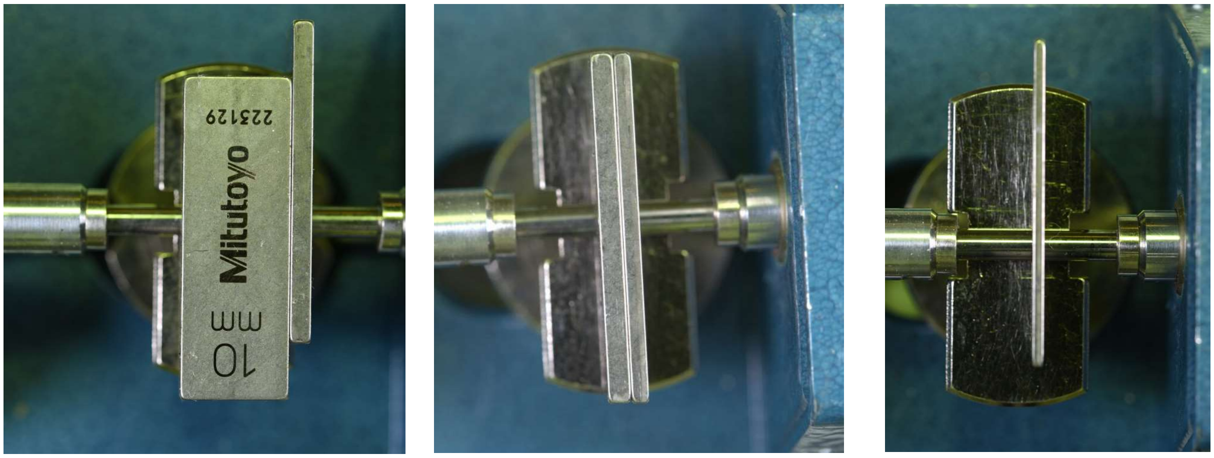


Figure 7. In-cell setup including the jaw gauge with digital indicator and the copy stand.

5.1.2 Procedure

The dimensional measurements follow the steps described in the LAMDA dimensional inspection guideline document [5]. Calibration of the jaw gauge was performed before and after each set of measurements and after every 5–6 measurements. The calibration used gauge blocks with dimensions as close as possible to the dimensions being measured: a 10+2 mm gauge blocks for the length measurements, a 2+1.5 mm gauge blocks for the width measurements, and a 1 mm gauge block for the thickness measurements (see Figure 8). At the beginning of each set of measurements, the gauge blocks were placed with clearance between the anvils. The anvils were then tightened on the gauge blocks such that the lever was pushed back 1 mm, and the digital indicator was set to the dimensions of the gauge blocks. The lever was moved a few times to ensure that the gauge blocks were well seated on the stage and the dimension read on the digital indicator stayed steady.



(a) (b) (c)

Figure 8. Calibration with gauge blocks for (a) the length measurements, (b) the width measurements, and (c) the thickness measurements.

After calibration was performed and the gauge blocks were removed from the jaw gauge, the lever was delicately moved to set the absorber specimen between the anvils to start recording the specimen dimensions. The specimen was then slowly moved on the stage while moving the lever, to place the next measurement point between the anvils and record the measurements. The same measurement points as those collected pre irradiation were recorded post irradiation (see Figure 9 [2]). APPENDIX B shows pictures of the various measurement points collected for one specimen in cell. Figure 10 shows a hot cell operator working with the jaw gauge to perform the dimensional measurements of the absorber material specimens.

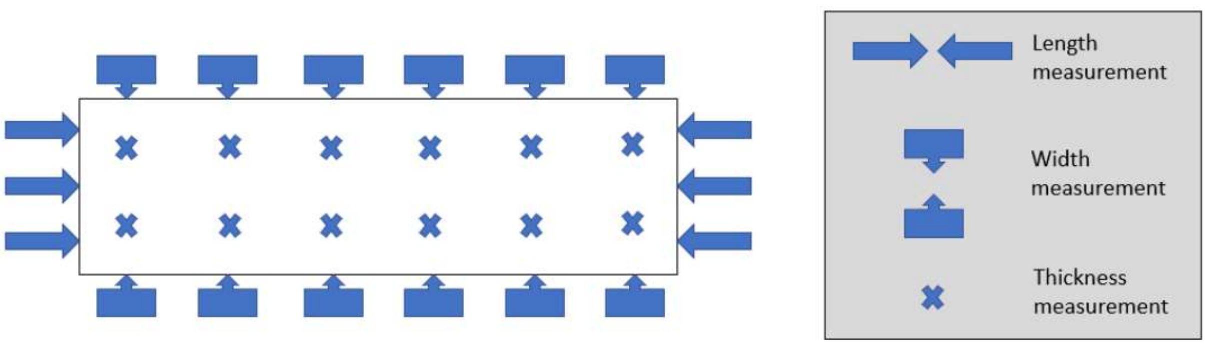


Figure 9. Locations of the different dimensional measurements on one specimen [2].

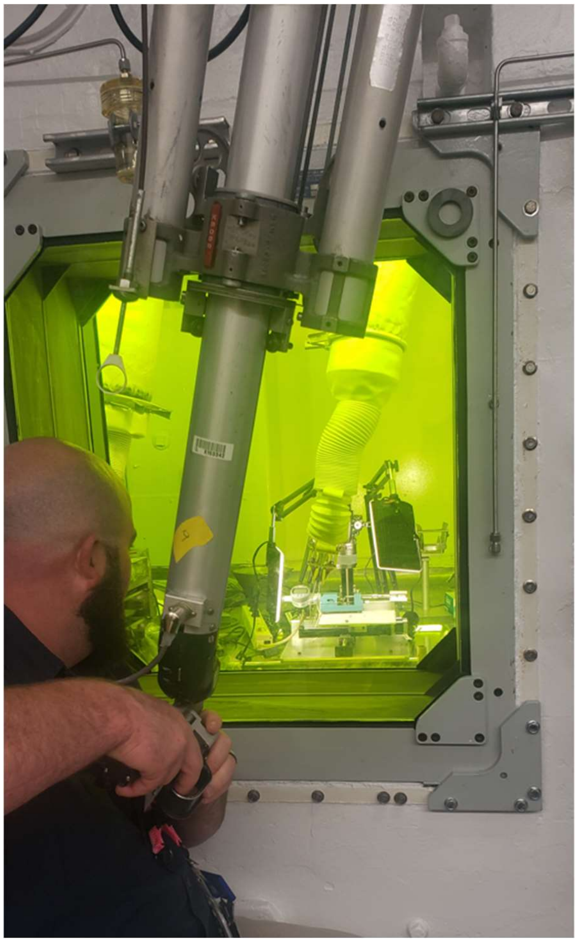
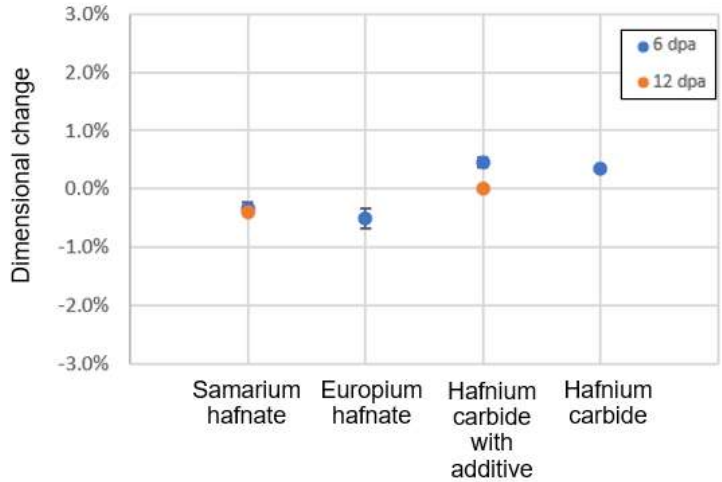


Figure 10. Hot cell operator performing the dimensional inspection of the absorber material specimens.

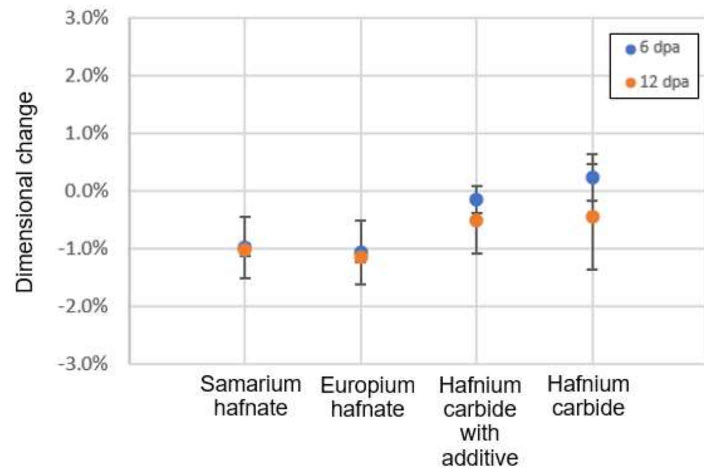
5.2 RESULTS

The dimensional measurements performed in-cell were recorded for each specimen and are listed in APPENDIX C. Some specimens broke during the measurements, and thus not all the data could be recorded. The length measurements were the most affected because broken specimens did not provide a straight edge for length measurements on several pieces. However, width and thickness were measured even on broken pieces of specimens. In other cases, some data are missing because of issues with setting the specimen on the gauge at the desired measurement location. It was decided to move forward with additional measurements rather than risk breaking the specimen on the collection of one data point.

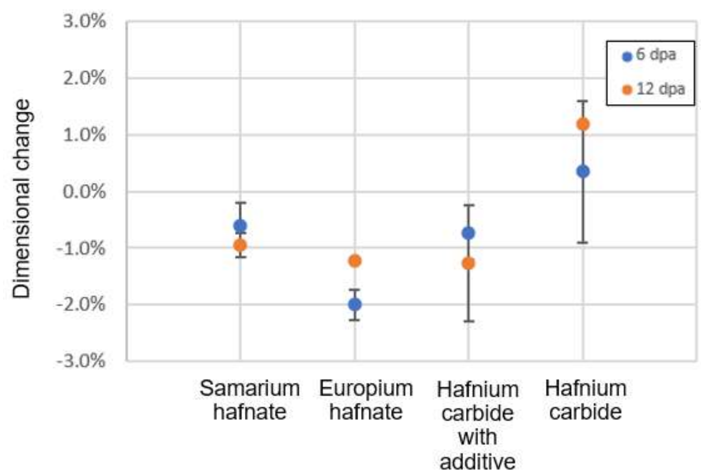
Figure 11 shows the length, width, and thickness changes for the four different types of absorber materials after irradiation at 6 and 12 dpa. Dimensional changes do not seem to vary with the irradiation dose for all four types of specimens, and overall no significant dimensional change was observed for all types of specimens.



(a) Length



b) Width



c) Thickness

Figure 11. Dimensional change in (a) length, b) width, and c) thickness of the absorber material specimen after irradiation at different two doses.

6. CONCLUSIONS

Two irradiation capsules containing absorber material specimens were irradiated in HFIR to irradiation damage levels of 6 and 12 dpa, respectively. The goal of this irradiation was to study the dimensional change after irradiation of four types of absorber material candidates: samarium hafnate, europium hafnate, hafnium carbide with additive, and hafnium carbide. After irradiation, the capsules were shipped to the hot cell facility for disassembly. The TMs were recovered and analyzed via dilatometry to confirm the irradiation temperature. The dilatometry results indicate that the experimental average temperature of the absorber material specimens was 305°C and 384°C for the 6 dpa and 12 dpa capsules, respectively. Most of the specimens were recovered intact upon disassembly and were dimensionally measured using a jaw gauge in cell. Several length, width, and thickness measurements were recorded and compared to similar measurements performed pre irradiation to estimate the dimensional change of the absorber materials post irradiation. No significant dimensional change was observed for all four absorber materials at both irradiation damage levels.

7. REFERENCES

[1] N. Cetiner, C. Petrie, J. Burns, A. Le Coq, K. Linton, J. Stevens, "Design and Thermal Analysis for Irradiation of Absorber Material Specimens in the High Flux Isotope Reactor," ORNL/SPR-2018/1038, November 2018.

[2] A. Le Coq, N. Cetiner, J. Burns, C. Petrie, K. Linton, J. Stevens, "Assembly of Capsules for Irradiation of Absorber Material Specimens in the High Flux Isotope Reactor," ORNL/SPR-2019-1312, September 2019.

[3] A.A. Campbell, W.D. Porter, Y. Katoh, L.L. Snead, "Method for analyzing passive silicon carbide thermometry with a continuous dilatometer to determine irradiation temperature," Nuclear Instruments and Methods in Physics Research B, 370 (2016).

[4] K.G. Field, J.L. McDuffee, J.W. Geringer, C.M. Petrie, Y. Katoh, "Evaluation of the continuous dilatometer method of silicon carbide thermometry for passive irradiation temperature determination," Nuclear Instruments and Methods in Physics Research B, 445 (2019).

[5] J.E. Schmidlin et al., Dimensional Inspection Guideline for Irradiated Sinosteel AMC Modulus Bars and Thermal Diffusivity Disks, LAMDA document no. MST-SINO-SOG-001, June 2017.

APPENDIX A. ABS01 AND ABS02 IRRADIATION HISTORY

APPENDIX A. ABS01 AND ABS02 IRRADIATION HISTORY

Location Data for Experiment ID: ABS01

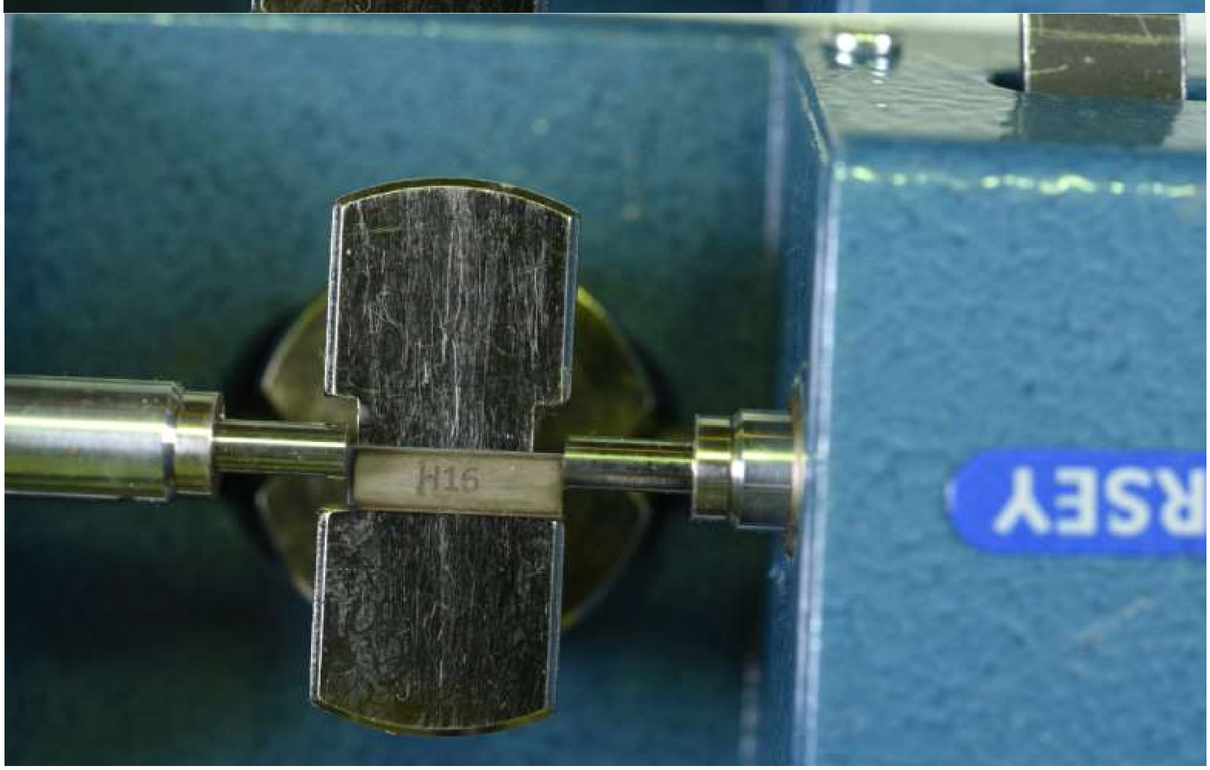
Cycle	Cycle Status	Location	Position	Accum. MWD
488A (06/09/20-06/09/20)	Complete	G4	5	14.06 [Cycle: 14.0600]
488B (06/12/20-07/07/20)	Complete	G4	5	2164.62 [Cycle: 2150.5600]
489 (08/18/20-09/12/20)	Complete	G4	5	4318.86 [Cycle: 2154.2400]
490A (02/23/21-02/23/21)	Complete	G4	5	4325.76 [Cycle: 6.9000]
490B (02/25/21-02/25/21)	Complete	G4	5	4348.09 [Cycle: 22.3300]
490C (03/02/21-03/27/21)	Complete	G4	5	6426.13 [Cycle: 2078.0400]
491 (04/13/21-05/08/21)	Complete	G4	5	8590.08 [Cycle: 2163.9500]
492 (05/25/21-06/19/21)	Complete	G4	5	10755.74 [Cycle: 2165.6600]
493 (06/29/21-07/25/21)	Complete	G4	5	12939.77 [Cycle: 2184.0300]

Location Data for Experiment ID: ABS02

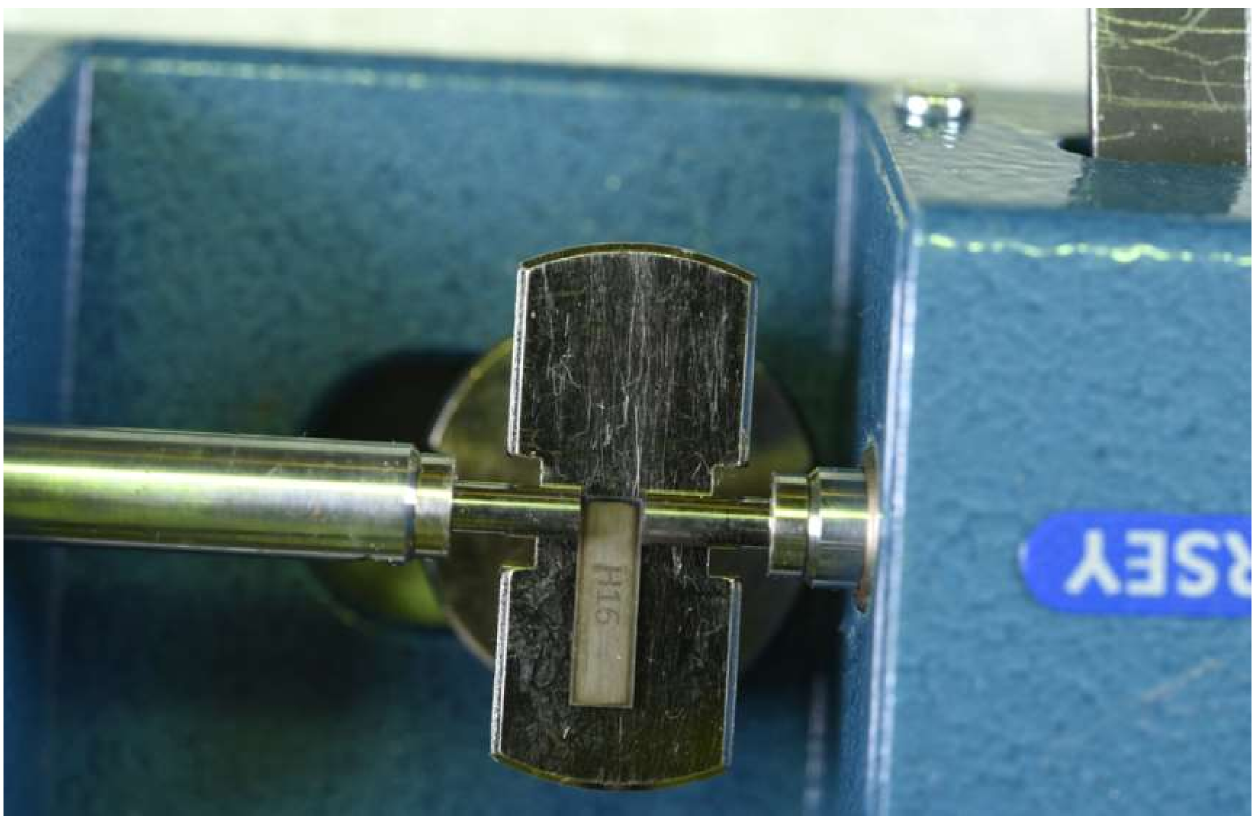
Cycle	Cycle Status	Location	Position	Accum. MWD
488A (06/09/20-06/09/20)	Complete	G7	5	14.06 [Cycle: 14.0600]
488B (06/12/20-07/07/20)	Complete	G7	5	2164.62 [Cycle: 2150.5600]
489 (08/18/20-09/12/20)	Complete	G7	5	4318.86 [Cycle: 2154.2400]
490A (02/23/21-02/23/21)	Complete	G7	5	4325.76 [Cycle: 6.9000]
490B (02/25/21-02/25/21)	Complete	G7	5	4348.09 [Cycle: 22.3300]
490C (03/02/21-03/27/21)	Complete	G7	5	6426.13 [Cycle: 2078.0400]
491 (04/13/21-05/08/21)	Complete	G7	5	8590.08 [Cycle: 2163.9500]
492 (05/25/21-06/19/21)	Complete	G7	5	10755.74 [Cycle: 2165.6600]
493 (06/29/21-07/25/21)	Complete	G7	5	12939.77 [Cycle: 2184.0300]
494 (08/09/21-09/04/21)	Complete	G7	5	15134.98 [Cycle: 2195.2100]
495 (09/21/21-10/17/21)	Complete	G7	5	17337.8 [Cycle: 2202.8200]
496A (01/04/22-01/04/22)	Complete	G7	5	17343.947 [Cycle: 6.1470]
496B (01/06/22-01/16/22)	Complete	G7	5	18234.6 [Cycle: 890.6530]
496C (01/20/22-02/04/22)	Complete	G7	5	19548.42 [Cycle: 1313.8200]
497 (02/22/22-03/20/22)	Complete	G7	5	21731.76 [Cycle: 2183.3400]
498A (04/05/22-04/16/22)	Complete	G7	5	22627.67 [Cycle: 895.9100]
498B (04/22/22-05/07/22)	Complete	G7	5	23884.45 [Cycle: 1256.7800]
499 (09/27/22-10/23/22)	Complete	G7	5	26047.5 [Cycle: 2163.0500]

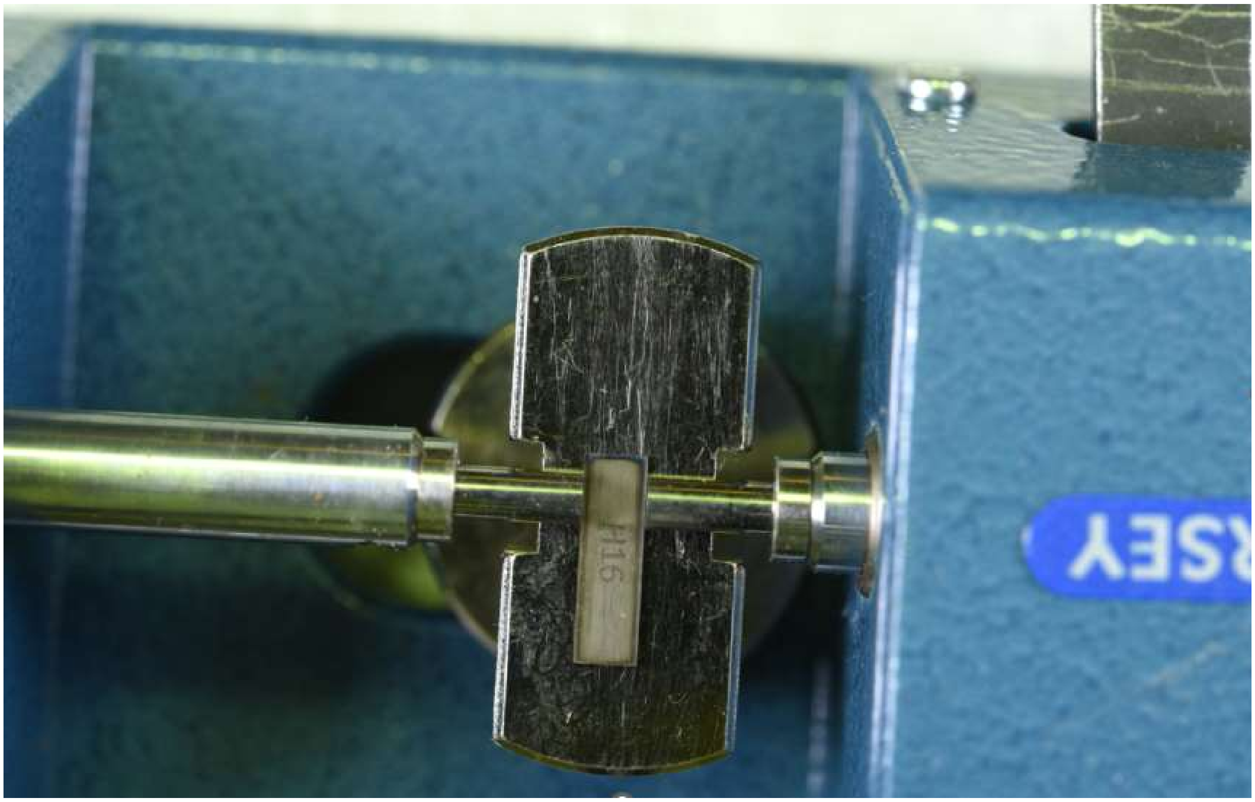
APPENDIX B. EXAMPLE OF DIMENSIONAL IN-CELL MEASUREMENTS PICTURES FOR ONE SPECIMEN

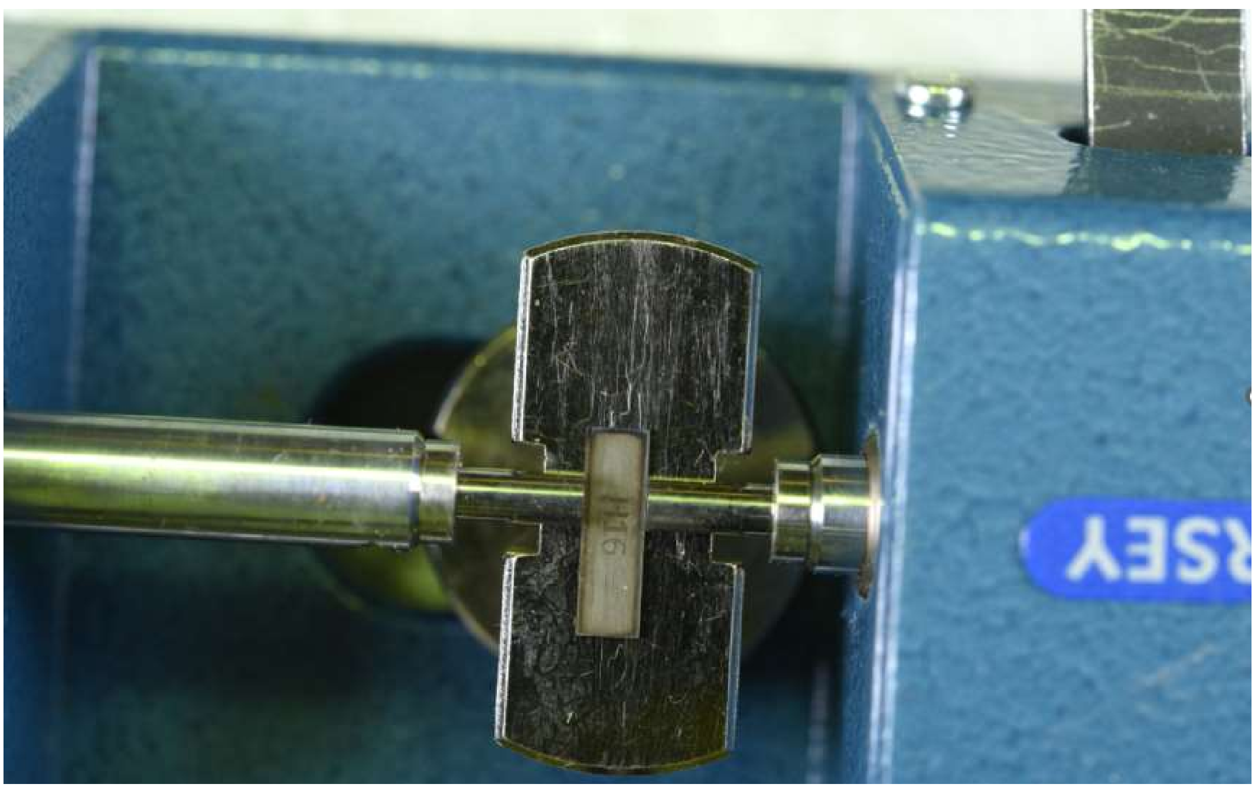
Length measurements

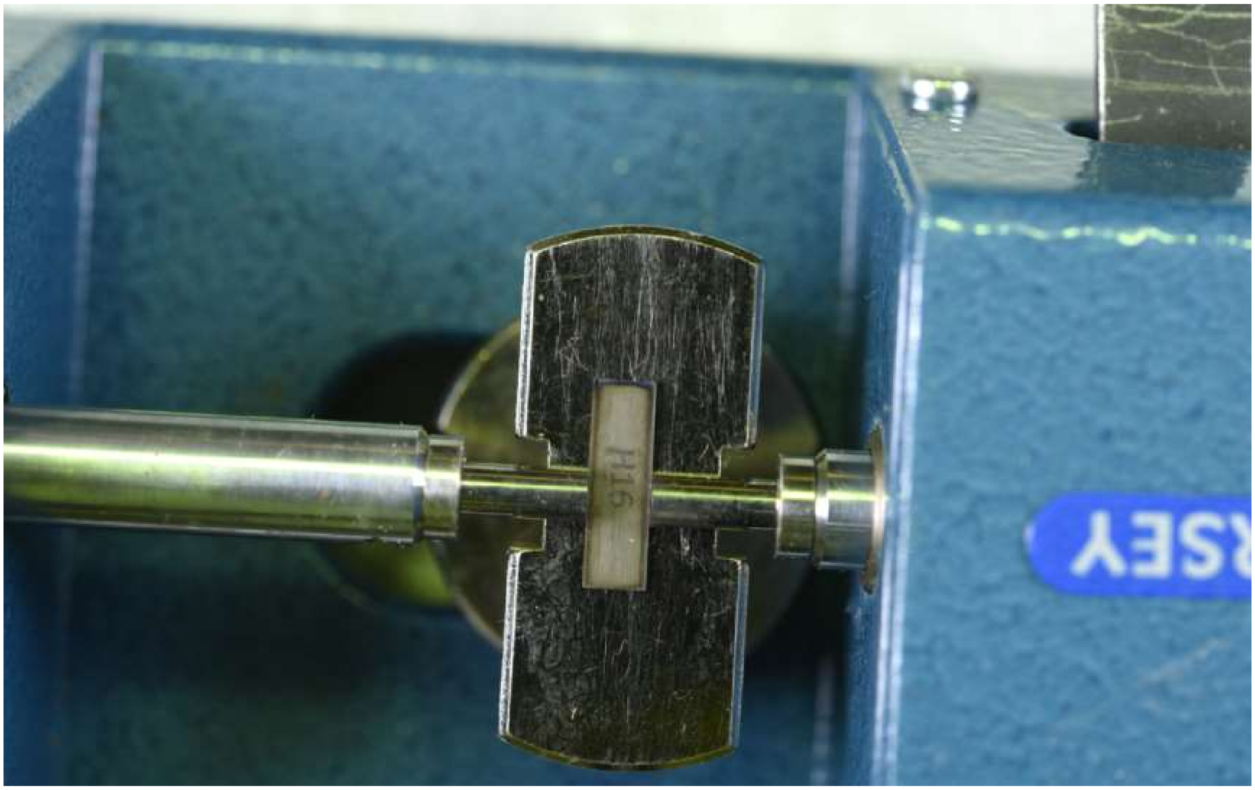


Width measurements



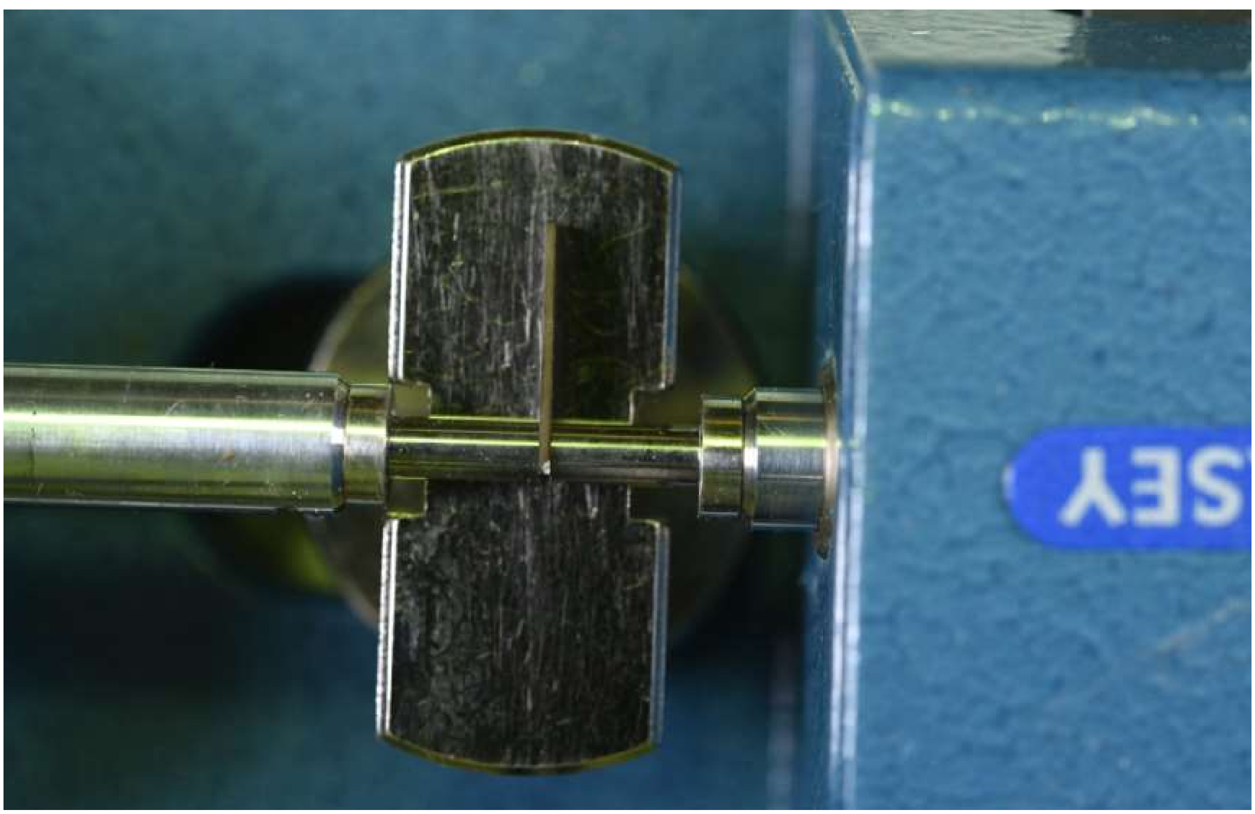


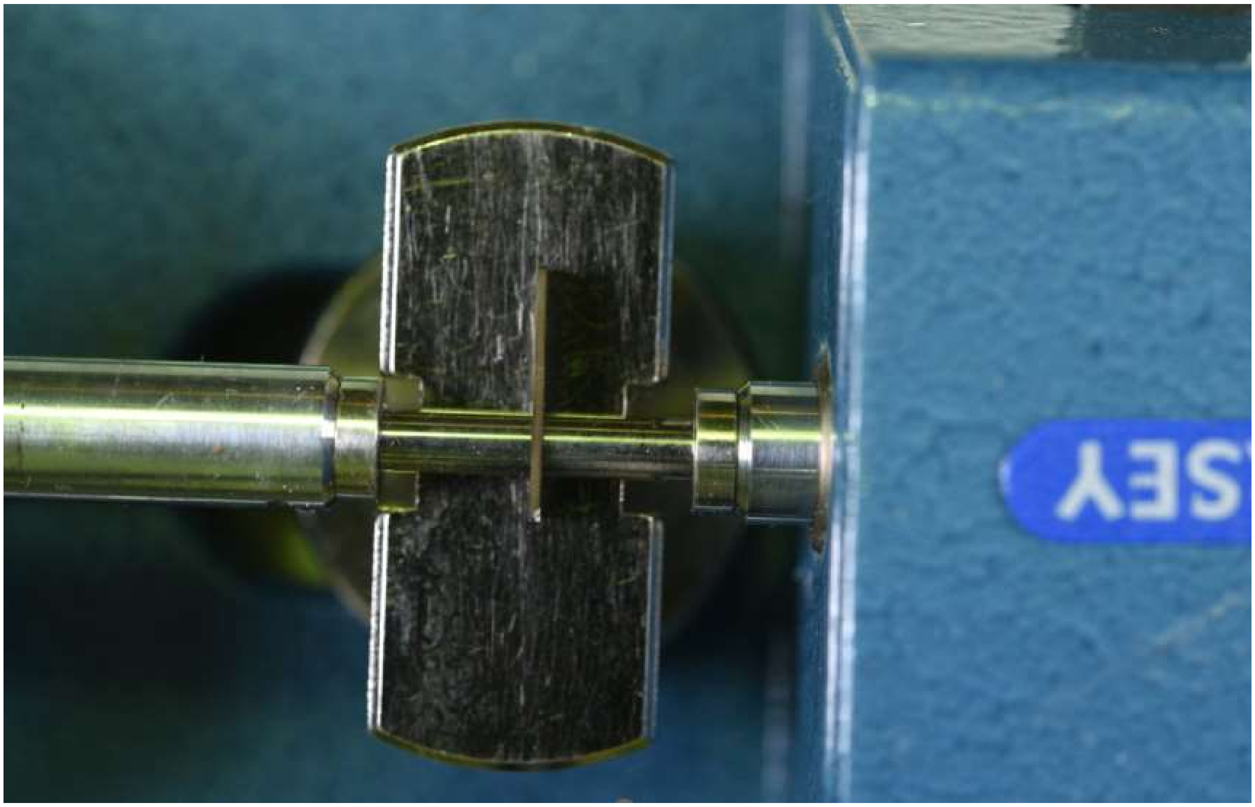


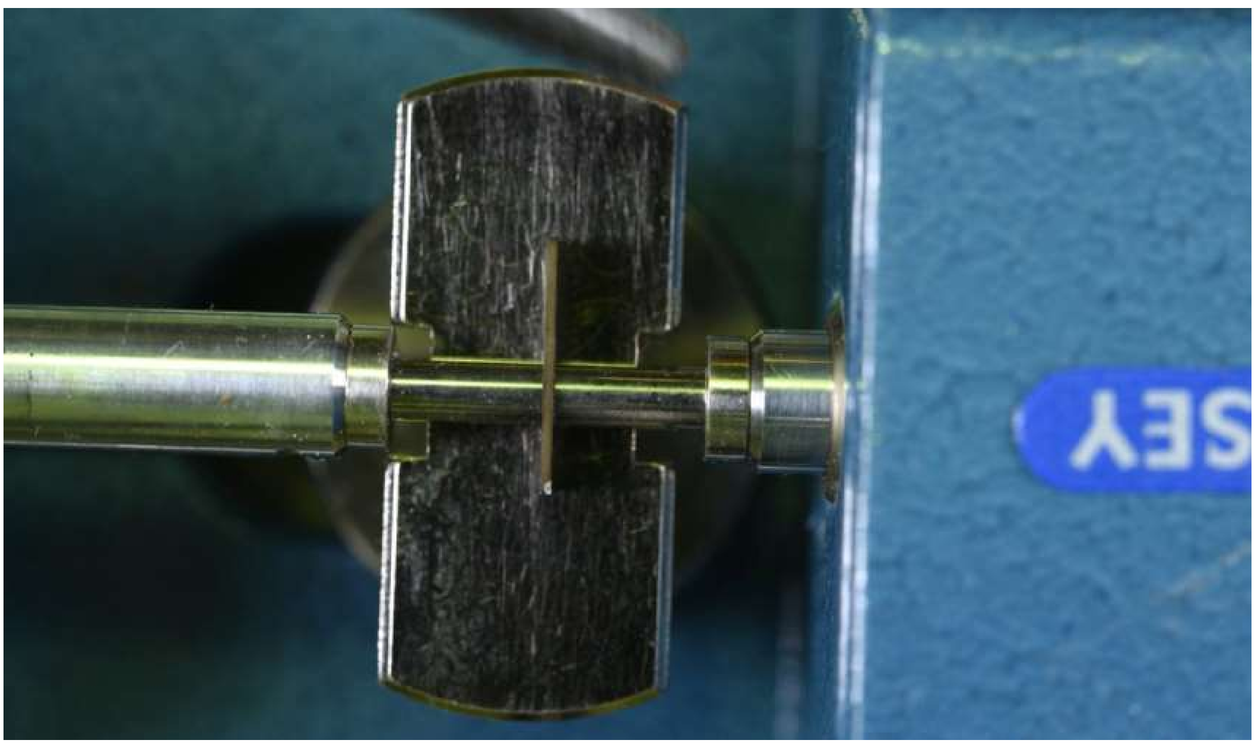

H15

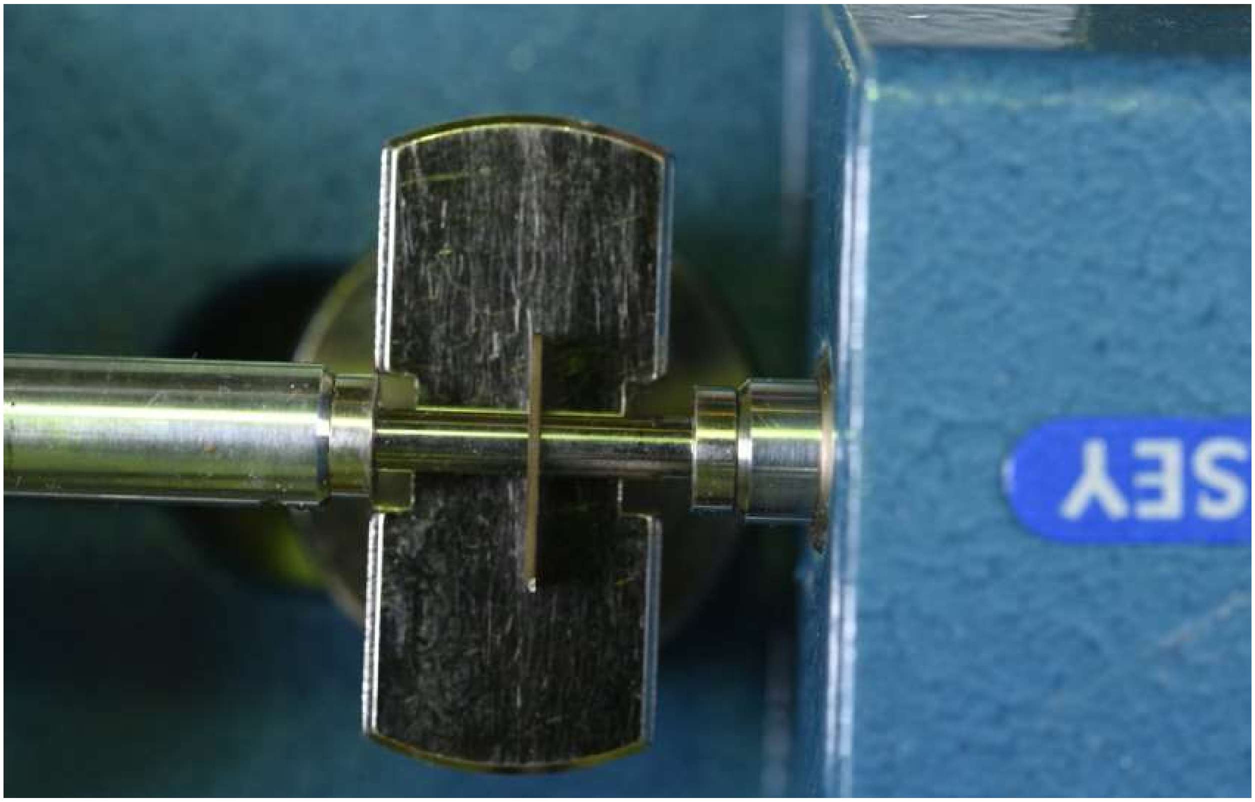

H16

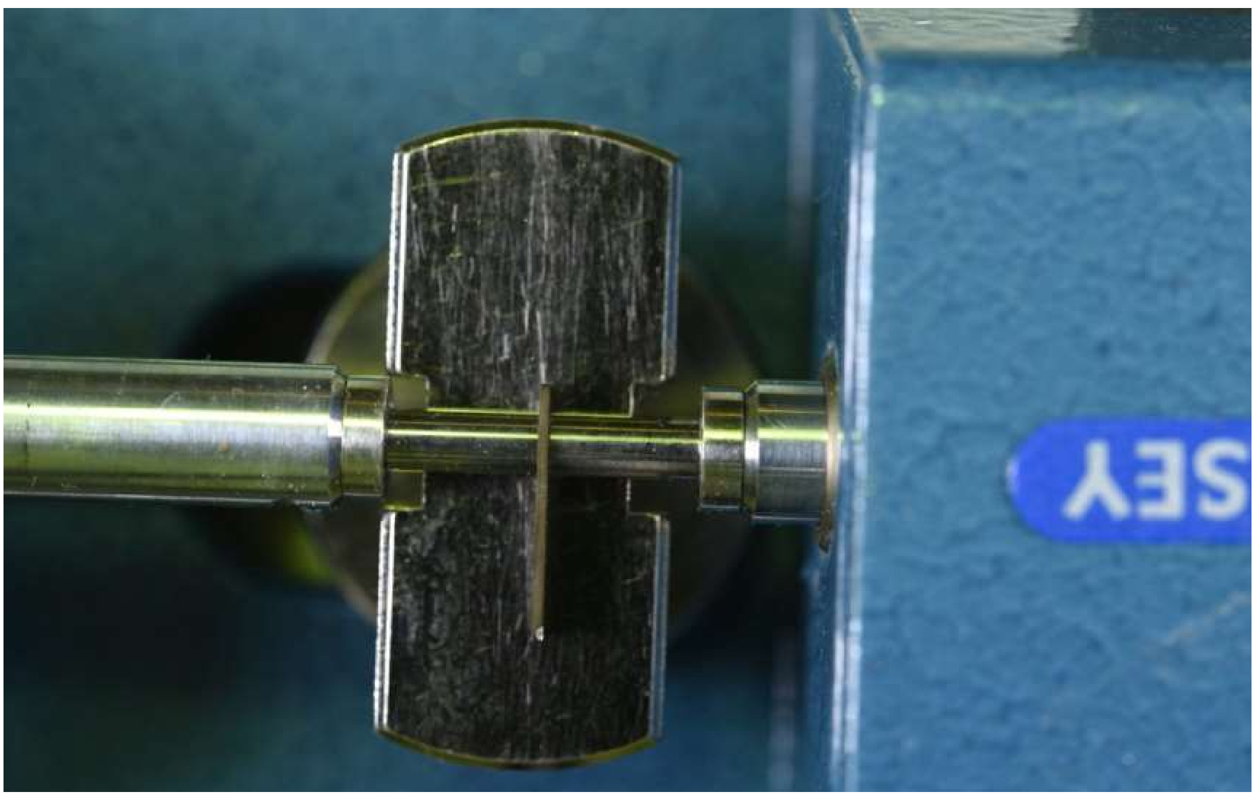
Thickness measurements

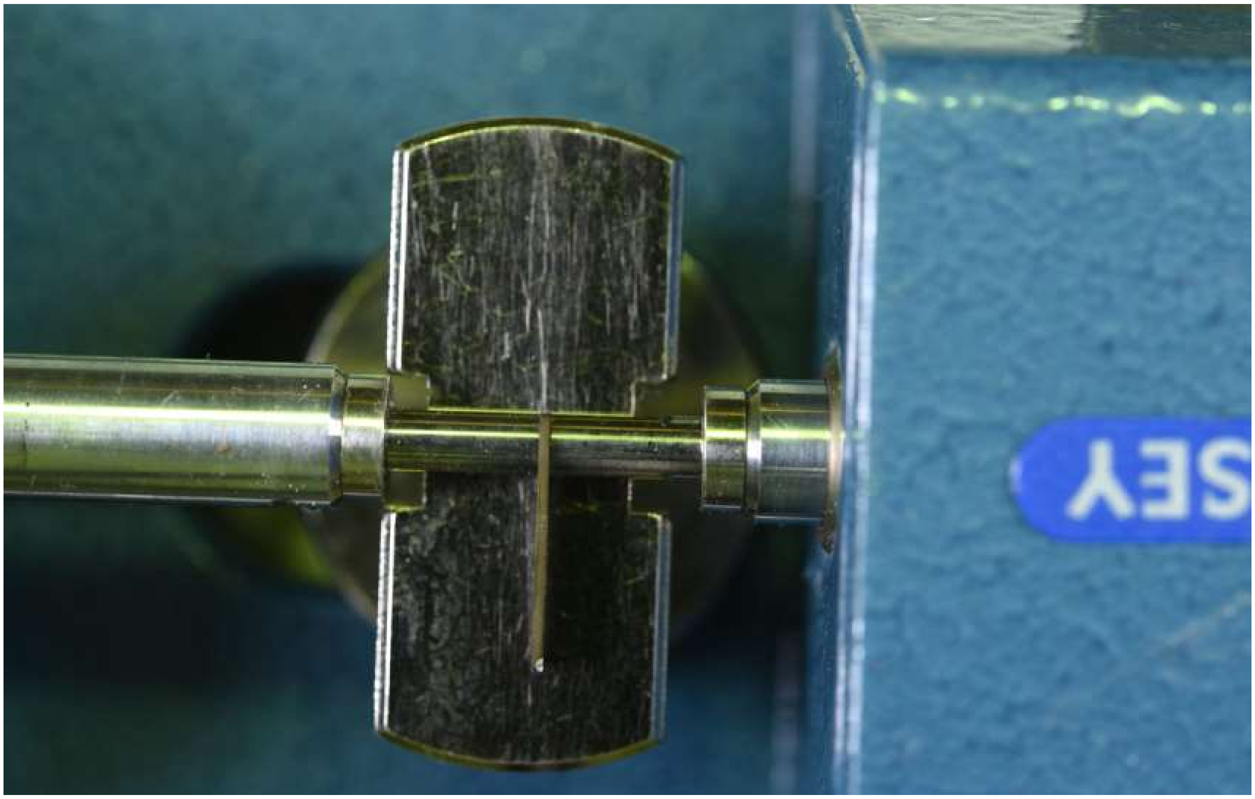


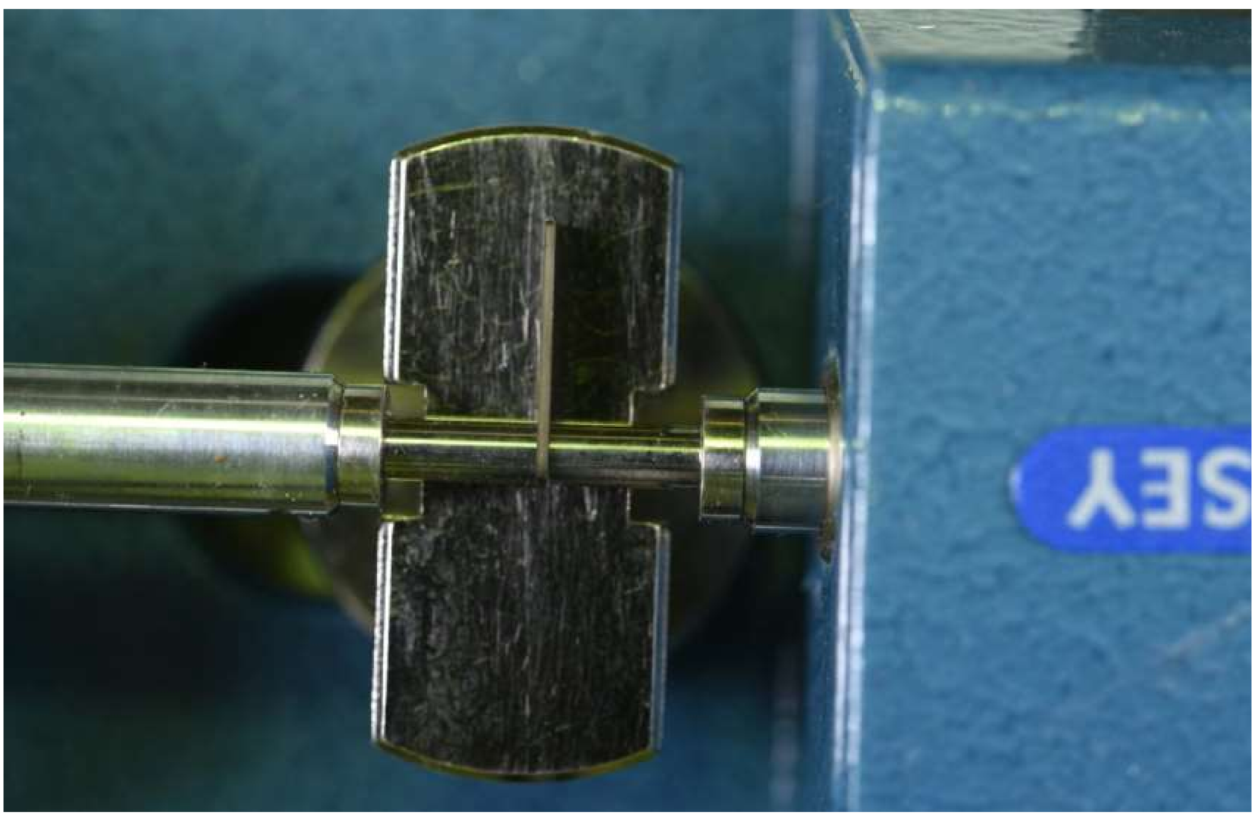


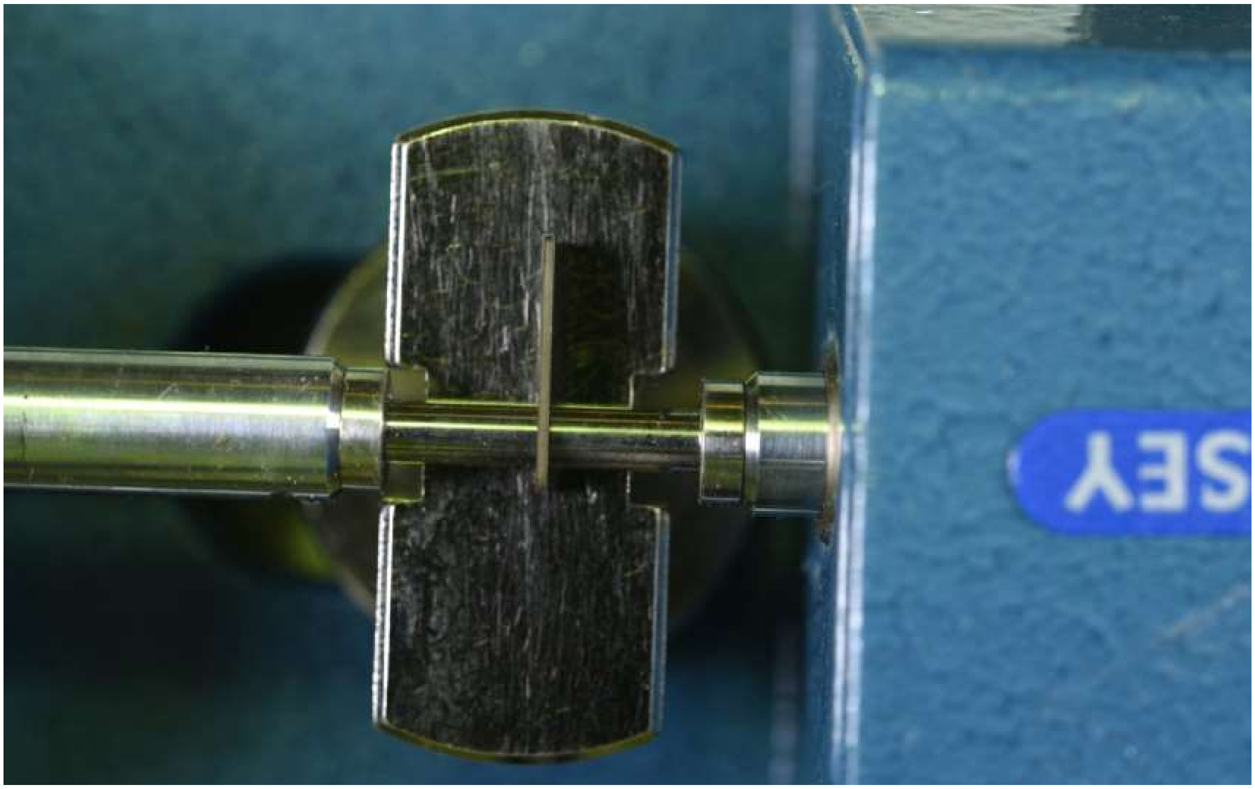


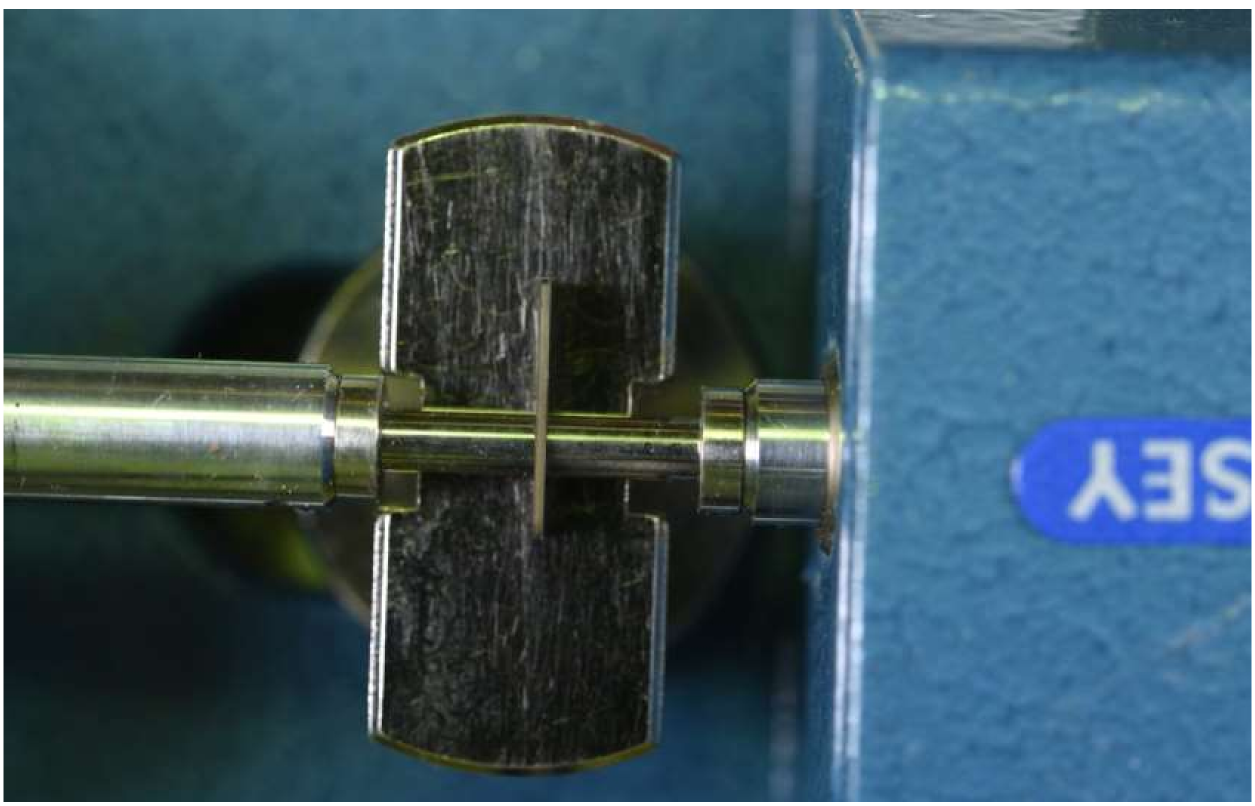


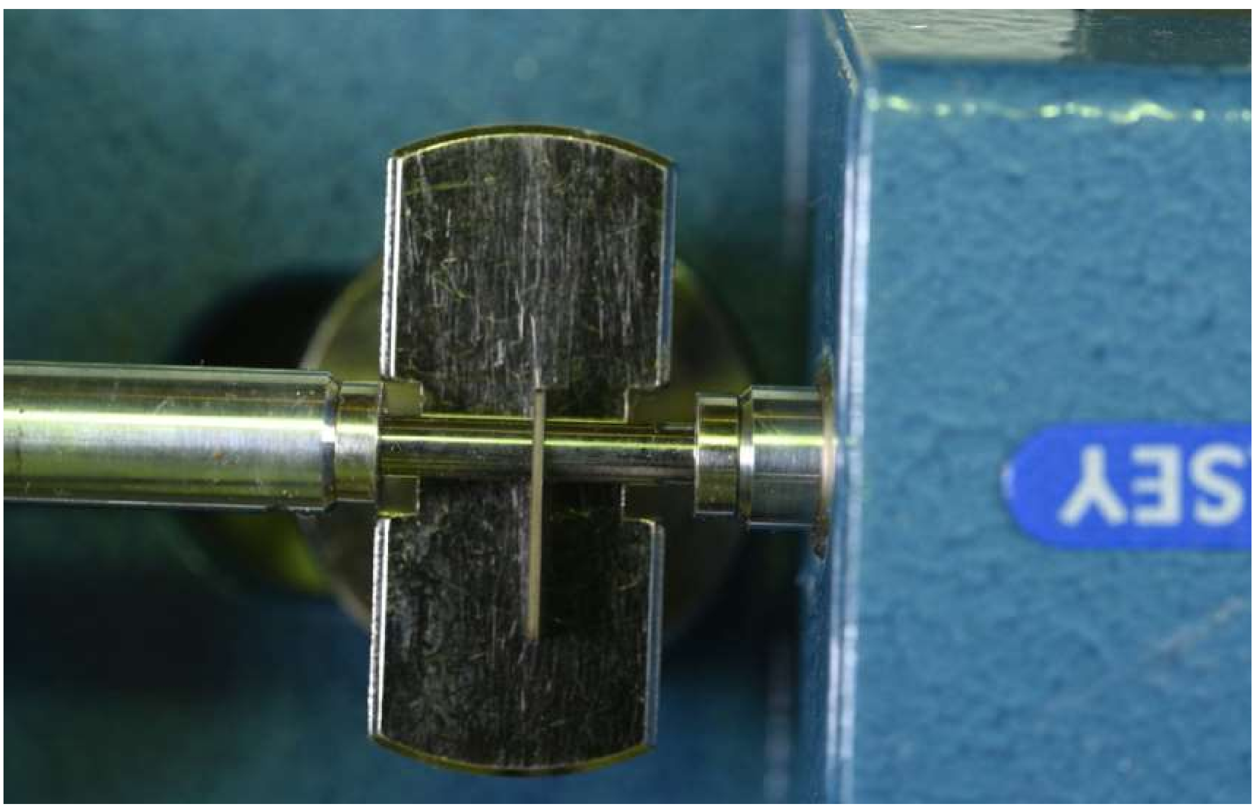


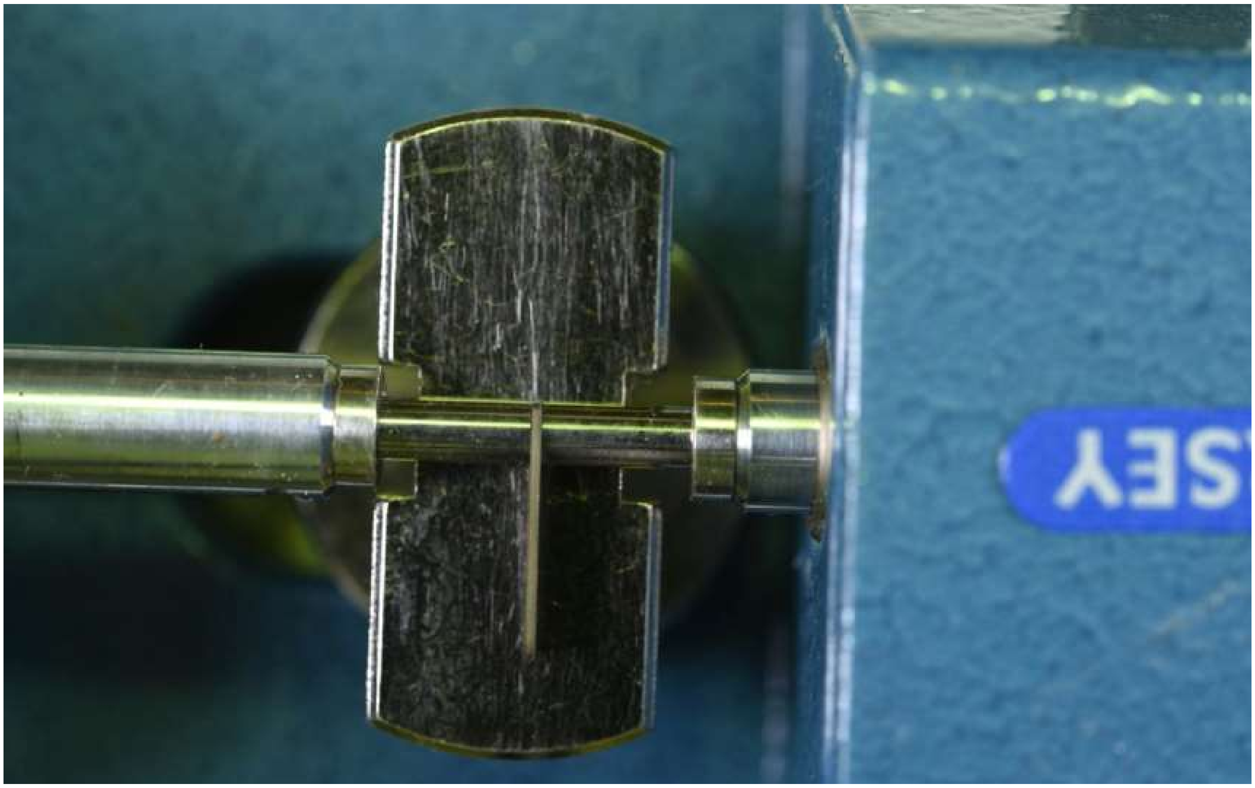












APPENDIX C. RESULTS OF THE POST-IRRADIATION DIMENSIONAL INSPECTION

APPENDIX C. RESULTS OF THE POST-IRRADIATION DIMENSIONAL INSPECTION

Post-irradiation data

Specimen	H15	H16	H17	H18	H23**	H24	M10	M11	M12	M13	M14	M22	E6	E7	E8	E9*	E21	S1	S2	S3	S5*
Length	calibration 10+2 mm																				
L1	N/A	12.008	N/A	N/A	N/A	N/A	12.046	12.006	missing	N/A	N/A	11.965	11.954	11.918	N/A	N/A	N/A	11.959	11.936	11.949	N/A
L2	N/A	12.005	N/A	N/A	N/A	N/A	12.043	12.003	12.024	N/A	N/A	11.968	11.951	11.932	N/A	N/A	N/A	11.970	11.939	11.947	N/A
L3	N/A	12.005	N/A	N/A	N/A	N/A	12.059	missing	12.024	N/A	N/A	11.966	missing	11.922	N/A	N/A	N/A	11.989	11.936	missing	N/A
calibration check	N/A	11.986	N/A	N/A	N/A	N/A	12.002	11.976	11.986	N/A	N/A	11.990	12.001	11.987	N/A	N/A	N/A	12.020	11.994	12.008	N/A
average L	N/A	12.006	N/A	N/A	N/A	N/A	12.038	12.005	12.024	N/A	N/A	11.966	11.953	11.924	N/A	N/A	N/A	11.973	11.951	11.948	N/A
Width	calibration 2+1.5 mm																				
W1	N/A	3.624	3.607	3.546	3.624	N/A	missing	missing	3.631	3.604	3.528	3.620	3.549	3.548	3.546	3.554	missing	3.575	3.559	3.555	3.554
W2	N/A	3.627	3.612	N/A	3.632	N/A	3.649	3.610	3.633	3.605	3.525	3.624	3.551	3.544	3.548	3.557	missing	3.579	3.560	3.554	3.557
W3	3.637	3.631	3.617	3.560	3.644	N/A	3.647	3.614	3.631	3.608	3.524	3.619	3.551	3.542	3.545	3.556	3.480	3.580	3.562	missing	3.556
W4	3.636	3.635	N/A	3.567	3.648	N/A	3.645	missing	3.632	3.609	3.522	3.617	3.551	3.543	3.544	3.550	3.480	3.578	missing	3.555	3.550
W5	3.637	3.628	3.632	3.566	3.632	N/A	3.640	3.611	3.628	3.610	3.520	3.610	3.552	3.543	missing	missing	3.476	3.577	3.560	3.555	missing
W6	3.638	3.640	N/A	3.565	3.630	N/A	3.631	3.592	3.624	3.606	3.512	3.603	3.551	3.541	missing	missing	3.473	3.578	3.559	3.555	missing
calibration check	N/A	3.502	3.504	3.485	3.505	N/A	3.503	N/A	3.492	3.503	3.457	3.507	3.481	3.501	3.499	3.498	3.505	3.500	N/A	3.488	3.498
average W	3.637	3.631	3.594	3.561	3.635	N/A	3.619	3.607	3.610	3.607	3.522	3.616	3.551	3.544	3.546	3.554	3.477	3.578	3.560	3.544	3.554
Thickness	calibration 1 mm																				
T1	N/A	0.518	0.521	0.551	0.542	N/A	0.520	0.510	0.515	0.517	0.511	0.517	0.509	0.516	0.518	0.513	0.516	0.516	0.512	0.518	0.513
T2	N/A	0.523	0.542	0.551	0.544	N/A	0.519	0.517	0.516	0.517	0.511	0.520	0.509	0.513	0.519	0.514	0.513	0.515	0.515	0.517	0.514
T3	0.512	0.521	N/A	0.540	0.559	N/A	0.519	0.518	0.534	0.521	0.511	0.515	0.511	0.515	0.515	0.515	0.513	0.513	0.516	0.518	0.515
T4	0.509	0.517	0.516	0.515	0.565	N/A	0.520	0.512	0.516	0.521	0.512	0.539	0.510	0.515	0.515	0.515	0.510	0.514	0.518	0.519	0.515
T5	0.512	0.518	N/A	0.513	0.570	N/A	0.519	0.517	0.515	0.528	0.513	0.537	0.511	0.515	missing	0.514	0.512	0.512	0.518	0.518	0.514
T6	0.512	0.521	N/A	0.514	0.562	N/A	0.519	0.517	0.514	0.527	0.515	0.515	0.509	0.516	missing	missing	0.512	0.514	0.516	0.516	missing
calibration check	0.995	0.999	N/A	0.998	N/A	N/A	N/A	0.995	0.994	N/A	N/A	0.979	1.007	1.000	0.995	0.995	0.994	N/A	0.999	1.002	0.995
	calibration 1 mm																				
T7	N/A	0.519	N/A	0.513	0.575	N/A	0.519	missing	0.519	0.519	0.507	0.539	0.510	0.499	0.514	0.514	0.509	0.514	0.515	0.518	0.514
T8	N/A	0.520	N/A	0.500	0.572	N/A	0.519	0.506	0.520	0.518	0.506	0.541	0.511	0.513	0.514	0.512	0.510	0.514	0.513	0.519	0.512
T9	0.515	0.520	N/A	0.500	0.579	N/A	0.519	0.505	0.520	0.521	0.504	0.542	0.512	missing	0.515	0.513	0.503	0.513	0.511	0.518	0.513
T10	0.519	0.520	N/A	0.500	0.578	N/A	missing	0.506	0.519	0.520	0.509	0.537	0.513	0.517	0.514	0.513	0.502	0.511	0.520	0.519	0.513
T11	missing	0.519	N/A	0.535	0.577	N/A	missing	0.506	0.521	0.525	0.503	0.539	0.513	0.505	missing	0.513	0.506	0.513	0.513	0.514	0.513
T12	0.514	0.522	N/A	0.533	0.573	N/A	missing	0.505	0.517	0.526	0.503	0.538	0.514	0.505	missing	missing	0.503	0.511	0.511	0.516	missing
calibration check	N/A	1.000	N/A	0.993	1.028	N/A	1.017	0.990	0.996	1.004	0.986	1.002	0.993	0.982	0.995	0.998	0.990	0.995	1.009	0.997	0.998
average T	0.513	0.520	0.526	0.522	0.566	N/A	0.519	0.511	0.519	0.522	0.509	0.532	0.511	0.512	0.516	0.514	0.509	0.513	0.515	0.518	0.514
Volume (mm^3)	N/A	22.66	N/A	N/A	N/A	N/A	22.62	22.12	22.52	N/A	N/A	23.00	21.69	21.62	N/A	N/A	N/A	21.99	21.90	21.91	N/A

* One piece of specimen was not able to be fully identified and could be part of E9 or S5 specimen. Thus, the dimensional measurements performed on this piece of specimen were recorded in the table for both E9 and S5.

** The thickness for this specimen is larger than the others, due to pieces of fiber tubes present on the specimens.

Comparison of post-irradiation data versus pre-irradiation data [2]

Specimen	H15	H16	H17	H18	H23**	H24	M10	M11	M12	M13	M14	M22	E6	E7	E8	E9	E21	S1	S2	S3	S5
Length																					
L1		0.38%					0.64%	0.35%				0.01%	-0.32%	-0.71%				-0.33%	-0.52%	-0.43%	
L2		0.34%					0.62%	0.33%	0.43%			0.03%	-0.37%	-0.61%				-0.24%	-0.48%	-0.43%	
L3		0.35%					0.73%		0.43%			0.01%		-0.68%				-0.08%	-0.52%		
average L		0.36%					0.56%	0.35%	0.44%			0.01%	-0.34%	-0.67%				-0.22%	-0.39%	-0.43%	
Width																					
W1		0.47%	0.25%	-1.64%	0.33%				0.11%	-0.08%	-1.20%	0.03%	-1.03%	-1.61%	-1.06%	-1.00%		-0.53%	-0.92%	-1.20%	-1.11%
W2		0.50%	0.25%		0.50%		0.47%	0.19%	0.17%	-0.33%	-1.29%	0.11%	-1.06%	-1.75%	-1.06%	-0.92%		-0.42%	-0.92%	-1.25%	-1.03%
W3	0.61%	0.47%	0.31%	-1.36%	0.72%		0.39%	0.28%	0.11%	-0.30%	-1.32%	0.03%	-1.09%	-1.78%	-1.12%	-1.22%	-0.32%	-0.39%	-0.86%		-1.09%
W4	0.50%	0.47%		-1.25%	0.75%		0.44%		0.22%	-0.28%	-1.35%	0.06%	-1.09%	-1.77%	-1.23%	-1.20%	-0.32%	-0.47%		-1.20%	-1.28%
W5	0.44%	0.22%	0.61%	-1.33%	0.28%		0.41%	0.33%	0.17%	-0.22%	-1.35%	-0.03%	-1.06%	-1.80%			-0.46%	-0.47%	-0.92%	-1.20%	
W6	0.39%	0.50%		-1.44%	0.19%		0.30%	-0.03%	0.19%	-0.14%	-1.49%	-0.08%	-1.06%	-1.83%			-0.49%	-0.45%	-0.95%	-1.20%	
average W	0.59%	0.44%	-0.33%	-1.38%	0.46%		-0.26%	0.18%	-0.38%	-0.23%	-1.33%	0.02%	-1.06%	-1.76%	-1.24%	-1.06%	-0.38%	-0.45%	-0.91%	-1.52%	-1.14%
Thickness																					
T1		0.19%	1.17%	6.58%	5.04%		0.58%	-0.78%	0.00%	0.58%	-0.78%	-2.64%	-2.30%	-0.39%	-0.58%	-0.97%	-0.96%	-0.58%	-0.97%	0.19%	-1.16%
T2		1.16%	4.84%	6.58%	4.42%		-0.38%	-0.39%	-1.15%	-1.52%	-2.67%	-2.26%	-2.68%	-1.35%	-0.38%	-0.96%	-1.54%	-0.77%	-0.580%	-0.39%	-1.15%
T3	-1.35%	0.58%		4.65%	7.92%		-1.52%	-0.96%	0.76%	-2.07%	-3.40%	-5.16%	-2.48%	-0.96%	-1.34%	-0.96%	-1.54%	-1.35%	-0.580%	-0.19%	-0.96%
T4	-2.30%	-0.19%	0.00%	-0.19%	9.50%		-0.76%	-1.35%	-2.83%	-1.70%	-3.58%	-0.74%	-2.49%	-0.96%	-1.53%	-1.15%	-2.11%	-0.96%	-0.19%	0.00%	-0.96%
T5	-1.73%	0.00%		-0.58%	10.25%		0.00%	-0.39%	-0.96%	1.15%	-1.35%	0.19%	-2.29%	-1.15%		-1.53%	-1.54%	-1.16%	-0.19%	-0.19%	-1.15%
T6	-1.16%	0.39%		-0.19%	8.49%		0.39%	0.19%	-0.58%	1.93%	-0.58%	-3.20%	-2.49%	-1.15%			-1.54%	-0.39%	-0.39%	-0.39%	
T7		0.39%		-0.77%	11.22%		0.58%		0.78%	0.97%	-1.93%	1.13%	-2.11%	-3.67%	-1.34%	-0.77%	-2.12%	-0.96%	-0.39%	0.19%	-0.96%
T8		0.58%		-3.10%	10.43%		-0.38%	-2.13%	0.00%	-1.89%	-3.99%	0.93%	-2.11%	-1.35%	-1.34%	-1.35%	-2.11%	-1.15%	-1.16%	0.00%	-1.54%
T9	-0.96%	0.58%		-3.10%	11.35%		-1.14%	-3.26%	-2.07%	-1.70%	-4.73%	0.56%	-2.29%		-1.34%	-1.35%	-3.46%	-1.16%	-1.73%	-0.39%	-1.35%
T10	-0.19%	0.39%		-3.10%	11.80%			-2.69%	-1.52%	-1.52%	-3.42%	-0.37%	-1.72%	-0.77%	-1.53%	-1.54%	-3.46%	-1.35%	0.19%	0.00%	-1.35%
T11		0.19%		3.88%	11.61%			-2.32%	0.77%	0.38%	-3.08%	0.94%	-1.72%	-3.07%		-1.72%	-2.69%	-0.97%	-1.35%	-0.96%	-1.54%
T12	-0.77%	0.58%		3.50%	10.62%			-1.75%	0.00%	1.94%	-2.71%	1.13%	-1.53%	-3.07%			-3.27%	-0.97%	-1.35%	-0.39%	
average t	-1.21%	0.40%	1.86%	1.18%	9.38%		-0.23%	-1.37%	-0.58%	-0.30%	-2.69%	-0.79%	-2.19%	-1.62%	-1.18%	-1.26%	-2.19%	-0.98%	-0.72%	-0.21%	-1.17%
Volume (mm^3)		1.20%					0.07%	-0.85%	-0.52%			-0.76%	-3.55%	-3.99%				-1.64%	-2.01%	-2.15%	

** The thickness change for this specimen is higher than for the others due to pieces of fiber tubes present on the specimens, and was not taken into account in the overall dimensional change study because of lack of relevance (see specimen picture below).