NRG

Evaluation of NICKel-based Materials for MSR applications: ENICKMA irradiation project

Young MSR conference, 6-8 June 2022
Lecco Italy

F. Naziris, naziris@nrg.eu
2.4852/22.238218

Nuclear. For life.

EU DuC= E001

Contents

Nuclear. For life.

NRG in a nutshell

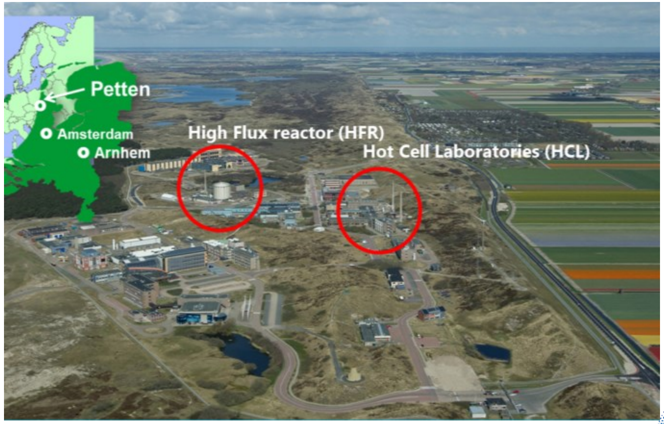
30,000
More patients helped every day

700
Motivated employees. Every day they make the world a little better

265
Reactor production days for research and medicines

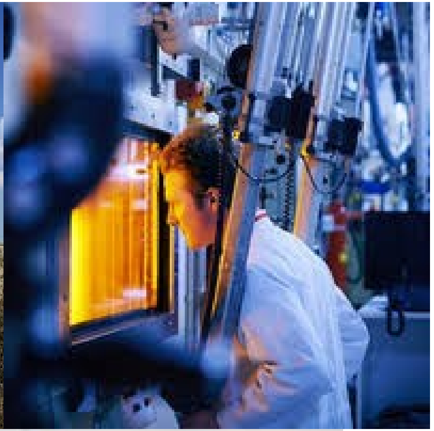
100%
Nuclear. For Life. Our R&D contributes to a healthier life, in both medicine as climate-neutral energy

- Main business areas: (a) Advancing Nuclear Medicine and (b) Ensuring Nuclear Performance
- Global market leader in producing medical isotopes
- Nuclear research and innovation projects → help industry as well as government for safe, reliable and efficient use of nuclear technology.
- Important nuclear infrastructure: (a) High Flux Reactor and (b) Hot Cell Laboratories in Petten.



For more details go to www.nrg.eu/en

FUELS & MATERIALS IRRADIATIONS



Material Irradiation Services

- Assess material behavior under accelerated irradiation conditions
- Low and high dose irradiation capacity
- Decades of experience with wide range of structural materials
- Extensive post-irradiation analysis capabilities in Hot Cell Laboratory

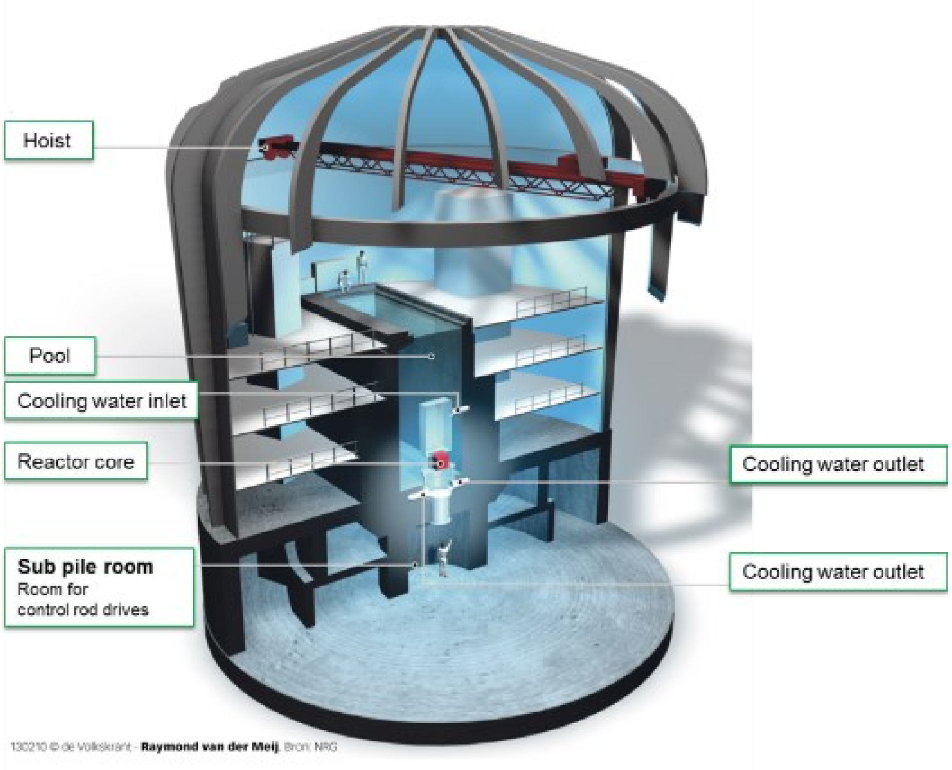
Fuel Irradiation Services

- Fuel testing and qualification for license applications
- New and existing concepts

Molten Salt Reactor Research Program

- MSR tailored irradiations
- Broad and ambitious public R&D and dedicated research for MSR developers
- From concept design to irradiation experiments

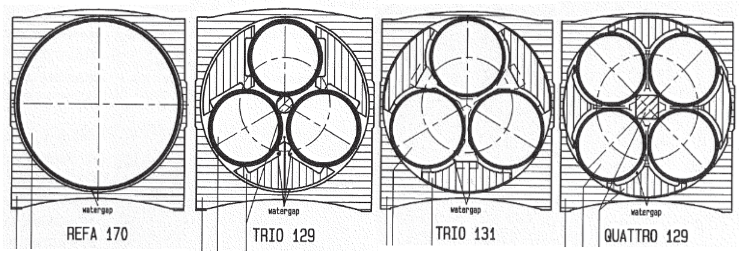
The High Flux Reactor



- High flux
- 45 MW thermal power
- Stable and constant flux profile in each irradiation position
- Main applications
  - Isotope production
  - Nuclear energy irradiation services
  - R&D
- 31 operation days per irradiation cycle, 9 cycles a year

HFR Standard Irradiation Rigs

- Outside is water-cooled, inside gas swept (mixtures of helium, neon, nitrogen)
- Instrumentation throughputs (temperature, presssure, …)
- Customisation possible

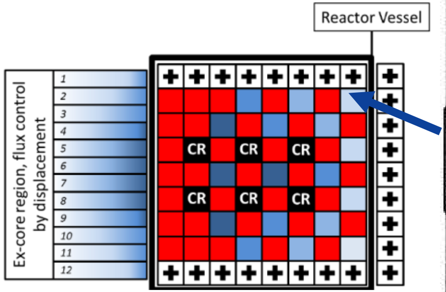


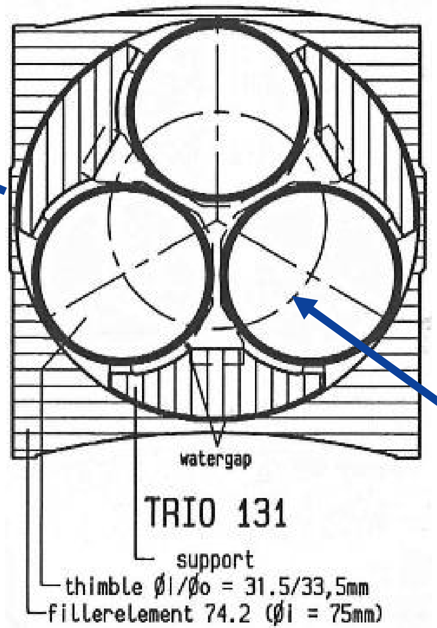
$Ø_{in}$ = 70 mm
$Ø_{out}$ = 72 mm

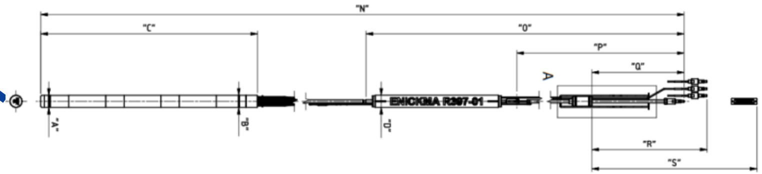
$Ø_{in}$ = 29 mm
$Ø_{out}$ = 32 mm

$Ø_{in}$ = 31.5 mm
$Ø_{out}$ = 33.5 mm

$Ø_{in}$ = 29 mm
$Ø_{out}$ = 31 mm







Current Program

Salient-01

Neutron & gamma irradiation of lithium fluoride and thorium fluoride salts in graphite crucibles

Salient-03

Determination of corrosion rates of structural materials when exposed to molten fuel salts under irradiation & introduces in-pile measurement of fission gas release

SAGA

Radiolytic production of F_2/UF_6

ENICKMA

He-induced embrittlement in Ni-based alloys

Lumos Waste

Development of disposal route

- Focus on irradiation technology
- Focus on generic topics (not specific for certain concepts)
- Ambitious program with limited funding, program open for partnering

NRG

ENICKMA: Evaluation of NICKel-based Materials

Structural materials → exposed to extreme conditions (radiation, corrosive environment, high temperature)

Material selection: mechanical properties should be retained and dimensional stability under both operation and abnormal conditions → investigation of material processes at micro and macroscale

Various MSR designs: consider Ni-based alloys for MSR applications (excellent high-temp. properties and corrosion resistance)

Irradiation data of Ni-based alloys limited → quantification based on time, temperature, energy spectrum, flux and composition

ENICKMA project

- Study irradiation properties of candidate structural materials for MSR applications
- Study the material degradation behavior under neutron irradiation and the underlying mechanism
- Publish useful material data and give insight for future MSR design

ENICKMA materials

- Hastelloy N (Haynes)
- Hstelloy 242 (Haynes)
- MONICR (CV Rez)
- HN80MTY (COMTES FHT)
- GH3535 (SINAP)
- 316 L (N) (CEA)

Radiation-Induced Embrittlement in Ni-based alloys

- For Ni-based alloys, **He-induced embrittlement** believed to be the main **degradation mechanism**

- He is produced with the fast neutron n,α reactions of

$$^{58}Ni + n_f \rightarrow {}^{55}Fe + {}^{4}He, \quad {}^{60}Ni + n_f \rightarrow {}^{57}Fe + {}^{4}He$$

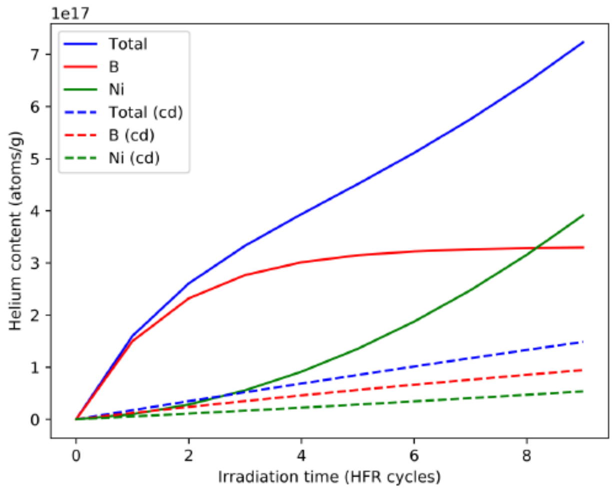
For thermal neutrons, He could be produced through the following reactions:

$$^{10}B + n \rightarrow {}^{7}Li + {}^{4}He$$

$$^{58}Ni + n \rightarrow {}^{59}Ni + \gamma, \quad {}^{59}Ni + n \rightarrow {}^{56}Fe + {}^{4}He$$

In the process of transmutation of Ni by thermal neutron, it requires production of ^{59}Ni first and results in an incubation time for helium production.

He bubbles at grain boundaries → embrittlement



Experimental method

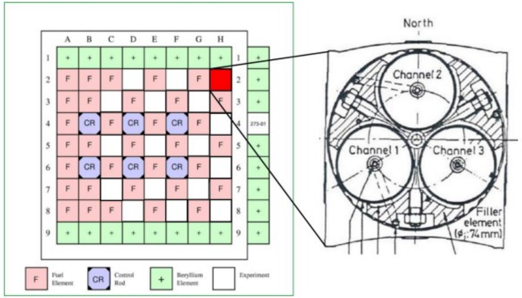


Figure 3: ENICKMA location in the HFR.

Irradiation

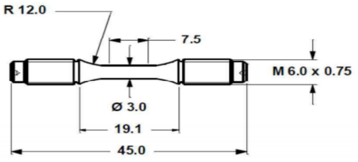
- 100 tensile and LCF samples
- Irradiation duration 9 HFR cycles
- Position H2, leg 1 of TRIO
- Up to 1E21 n/cm^2 thermal, 3E21 n/cm^2 fast (up to 50 appm helium , >1 dpa expected)
- Irradiation temperature 650°C-750°C

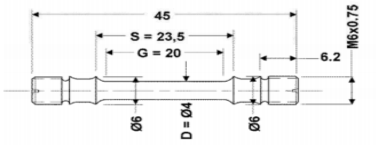
Oven tests

- Thermal annealing for 1 month at 800 °C
- Thermal annealing for 5 months at 650 °C
- Thermal annealing for 9 months at 650 °C

Planned tests

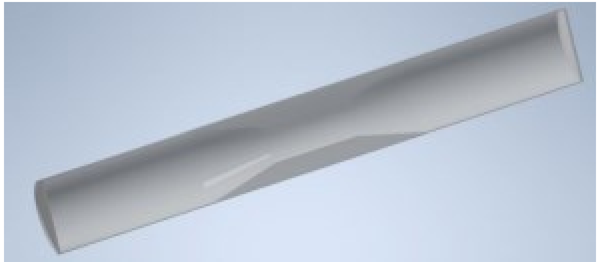
- Mechanical tests (tensile, LCF, SPT…) on as-received, annealed & irradiated specimens
- Correlation mechanical properties & microstructural changes (OM, SEM, TEM)

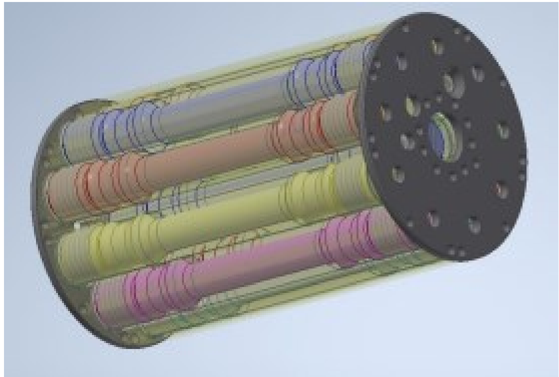




Irradiation facility

- 10 drums, each containing 10 specimen





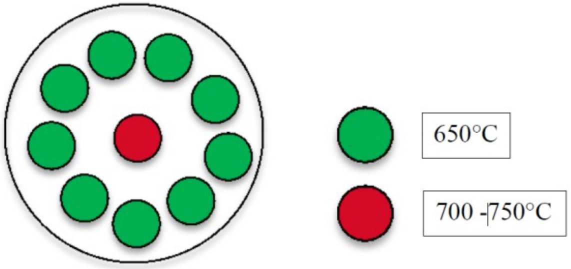
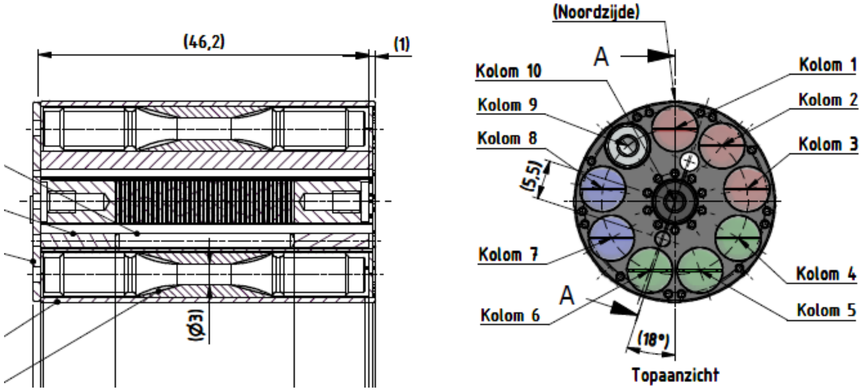


Figure 1: Cross section view of concept design of the irradiation rig.



Preliminary results

Test Matrix

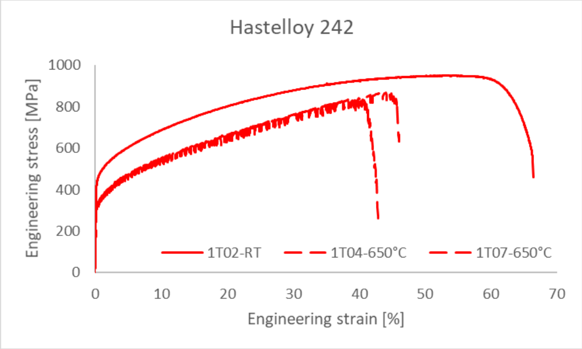
	As-received		Annealed at 800 °C for 1 month	
	RT	650 °C	RT	650 °C
Hastelloy N	2	2	2	1
Hastelloy 242	1	2	2	1

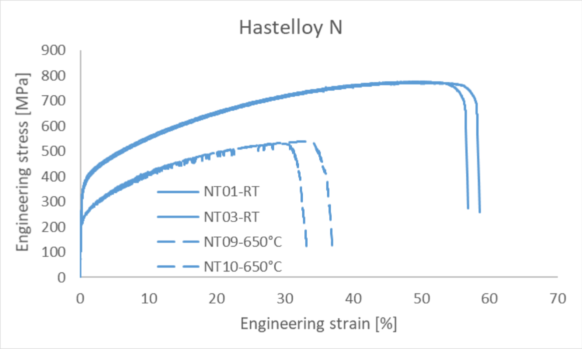
Chemical compositions

	Weight % Main Alloying Elements											
Alloy	Al	Co	Cr	Fe	Mn	Mo	Nb	Ni	Si	Ti	V	C
Hastelloy N	0.29	0.078	7.10	3.60	0.46	17.10	0.070	Bal.	0.31	0.002	0.005	0.059
Hastelloy 242	0.17	0.026	8.00	1.16	0.26	25.80	<0.001	Bal.	<0.02	0.001	0.002	0.002

As-received condition

Material	Test temperature [°C]	0,2% YS [MPa]	UTS [MPa]	UE [%]	TE [%]
Hastelloy N	RT	335	774	49	57,7
	650	224	534	31,2	35
Hastelloy 242	RT	**451**	**950**	52,6	66,2
	650	**328**	**851**	**41,8**	**44,2**

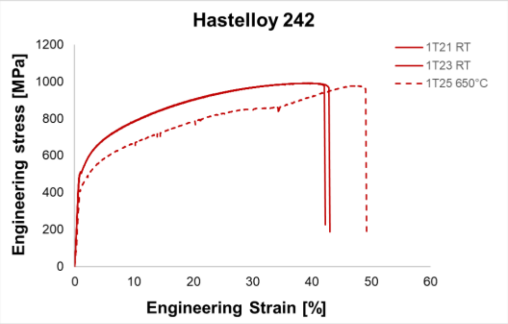


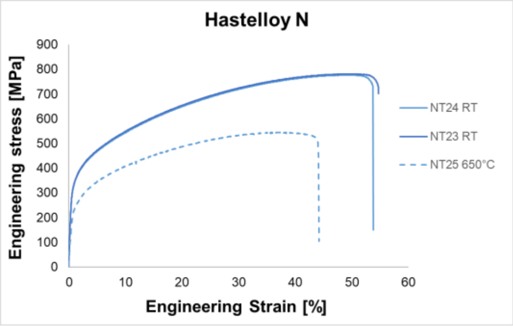


A serrated flow behaviour is observed for the high temperature tests, due to dynamic interaction between mobile dislocations and diffusion solute atoms during plastic deformation

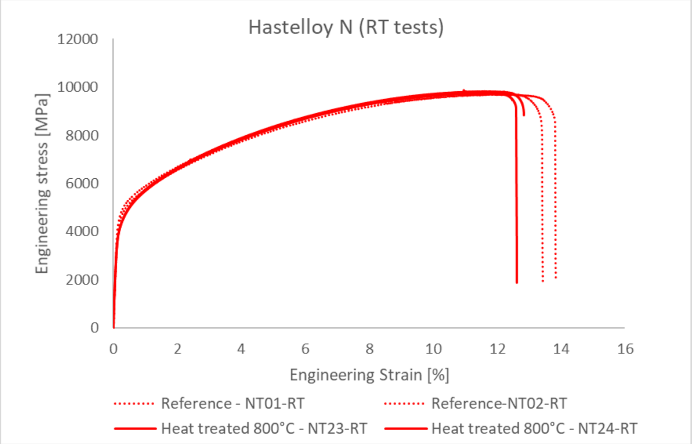
Tensile Test – 800 °C annealing

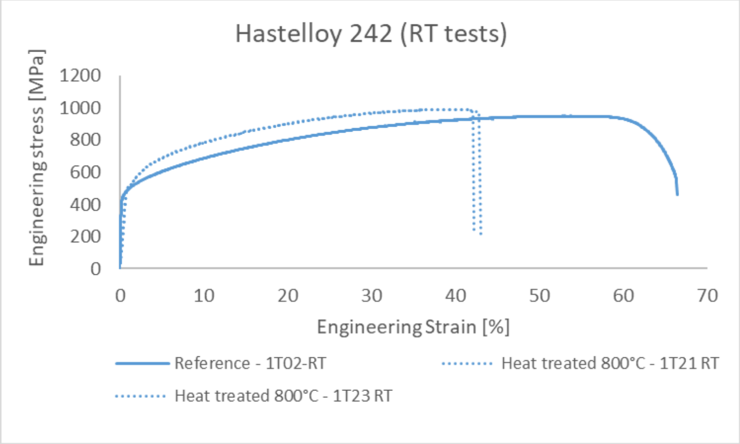
Material	Sample ID	Test temperature	0.2% YS (MPa)	UTS (MPa)	UE (%)	TE (%)
Hastelloy 242	1T21	RT	503	991	38,2	42,8
Hastelloy 242	1T23	RT	511	991	37,8	41,9
Hastelloy 242	1T25	650 ºC	419	977	45,6	48,8
Hastelloy N	NT23	RT	311	781	47,3	53,8
Hastelloy N	NT24	RT	304	777	48,2	53,6
Hastelloy N	NT25	650 ºC	192	544	35,7	44,0



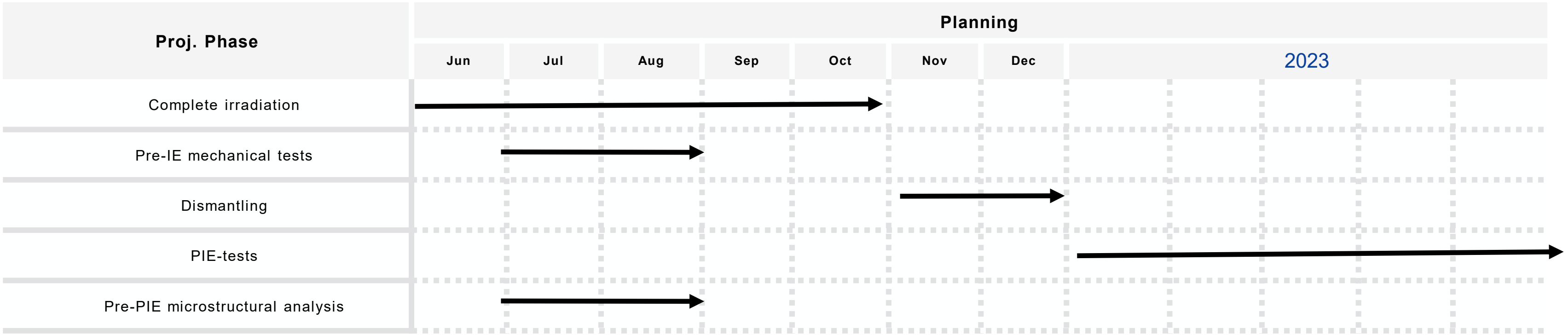


Comparison to as-received condition





Future work and planning



Questions?

Thank you for your attention

Dutch program overview

- Sponsored by the Dutch Ministry of Economic Affairs as part of a broader Nuclear Energy R&D program.
- In collaborations with JRC, TU Delft and CV Rez, which provide complementary competences
- Program objective: provide meaningful contribution to MSR technology development.
  - Obtain operational experience
  - Improve safety
  - Support materials development
  - Tackle waste issues
  - Integral Demonstration

Ministry of Economic Affairs of the Netherlands

JRC EUROPEAN COMMISSION

TU Delft Technische Universiteit Delft

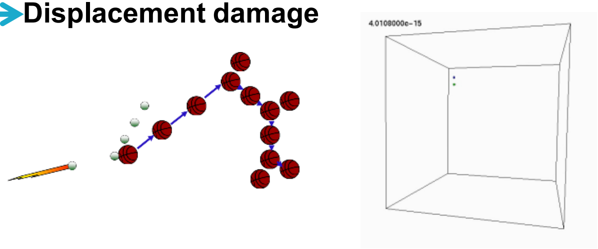
Centrum výzkumu Řež s.r.o. Research Centre Řež

NRG

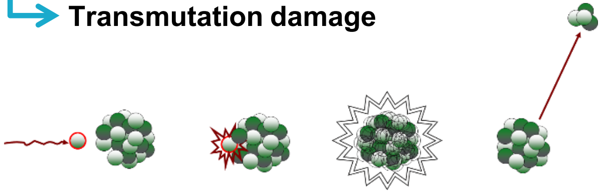
Damage mechanisms - Embrittlement

Radiation damage

Displacement damage



Transmutation damage



Binary collisions

1

PKA cascades, He production

2

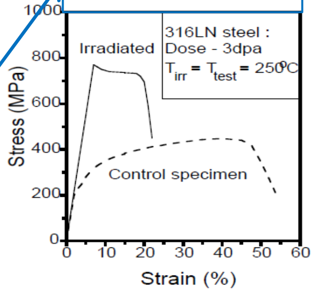
1A **point defects, small clusters, He atoms**

3 **mobility**

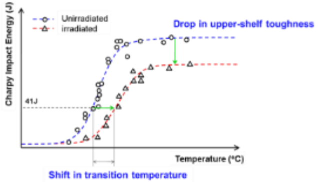
100 A **voids, bubbles, precipitates, dislocation loops**

Swelling

Hardening



Embrittlement



Influencing factors:

- Neutron spectrum
- Composition
- Time and Temperature

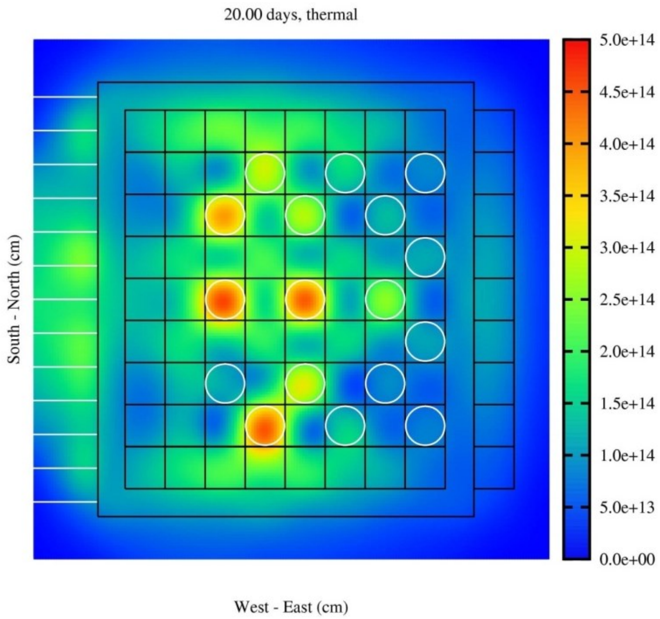


Figure 2-4: Cross sectional view of the HFR (thermal flux)

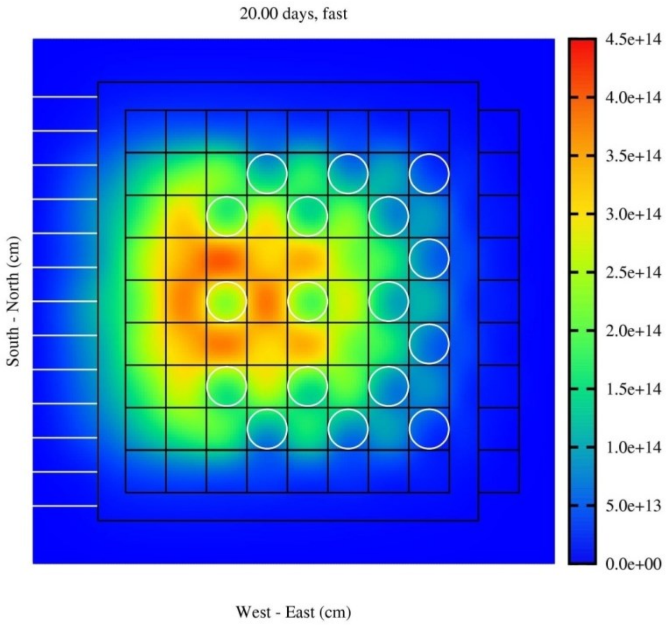


Figure 2-5: Cross sectional view of the HFR (fast flux)

Table 2 The effect of thermal neutron dose on the Total elongation of Hastelloy X tensile tested at ~1.1 × 10^{-4} s^{-1}.

T_{test} (K)	Thermal Neutron Dose (n/cm^2)	Calculated Helium (appm)	Total Elongation (%)
973	NA	0.04	30
	NA	0.4	20
	NA	4	8
1173	$2.7x10^{17}$	0.004	50
	$2.2x10^{18}$	0.04	40
	$2.4x10^{19}$	0.4	20
	$4.3x10^{20}$	5	7
	$2.0x10^{21}$	40	5
1273	$2.7x10^{17}$	0.004	40
	$2.2x10^{18}$	0.04	30
	$2.4x10^{19}$	0.4	6
	$4.3x10^{20}$	5	4

K. Watanabe, Y. Ogawa, M. Kikuchi and T. Kondo, Ductility Loss of Neutron-Irradiated Hastelloy-X at Elevated Temperatures, JAERI Research Report JAERI-M 8807 (1980)

Table 2: Neutron fluence (n cm^{-2}) after 9 HFR cycles averaged over four dummy QUATTRO legs in H4.

Axial boundaries (cm)		*Thermal*	*Fast*	*Total*	
Lower	*Upper*	*E<0.625 eV*	*E>0.1 MeV*	*No Cd*	*With Cd*
+20	+30	8.71E+20	1.30E+21	3.47E+21	2.60E+21
+10	+20	1.28E+21	2.18E+21	5.61E+21	4.34E+21
0	+10	1.68E+21	2.78E+21	7.24E+21	5.56E+21
-10	0	1.84E+21	2.99E+21	7.83E+21	5.99E+21
-20	-10	1.69E+21	2.73E+21	7.15E+21	5.47E+21
-30	-20	1.41E+21	1.95E+21	5.30E+21	3.89E+21

Table 3: Helium produced in the Ni-based alloy (atoms/g) after irradiation for 9 cycles. Total helium, and helium produced from only the boron and nickel is shown.

Axial boundaries (cm)		*No Cd*			*With Cd*		
Lower	*Upper*	*Total*	*Boron*	*Nickel*	*Total*	*Boron*	*Nicke.*
+20	+30	4.07E+17	3.06E+17	1.01E+17	6.75E+16	4.49E+16	2.22E+16
+10	+20	5.29E+17	3.23E+17	2.04E+17	1.09E+17	7.02E+16	3.80E+16
0	+10	6.62E+17	3.29E+17	3.32E+17	1.38E+17	8.80E+16	4.93E+16
-10	0	7.23E+17	3.29E+17	3.91E+17	1.49E+17	9.44E+16	5.35E+16
-20	-10	6.63E+17	3.29E+17	3.32E+17	1.36E+17	8.67E+16	4.88E+16
-30	-20	5.62E+17	3.26E+17	2.34E+17	9.96E+16	6.48E+16	3.43E+16

Table 5 He production in the material after 9 cycles of irradiation in HFR H4

boundaries (cm)		No Cd			With Cd			H content (appm)
Lower	Upper	Total	Boron	Nickel	Total	Boron	Nickel	
20	30	4.07E+17	3.06E+17	1.01E+17	6.75E+16	4.49E+16	2.22E+16	39.69
10	20	5.29E+17	3.23E+17	2.04E+17	1.09E+17	7.02E+16	3.80E+16	51.58
0	10	6.62E+17	3.29E+17	3.32E+17	1.38E+17	8.80E+16	4.93E+16	64.55
-10	0	7.23E+17	3.29E+17	3.91E+17	1.49E+17	9.44E+16	5.35E+16	70.50
-20	-10	6.63E+17	3.29E+17	3.32E+17	1.36E+17	8.67E+16	4.88E+16	64.65
-30	-20	5.62E+17	3.26E+17	2.34E+17	9.96E+16	6.48E+16	3.43E+16	54.80