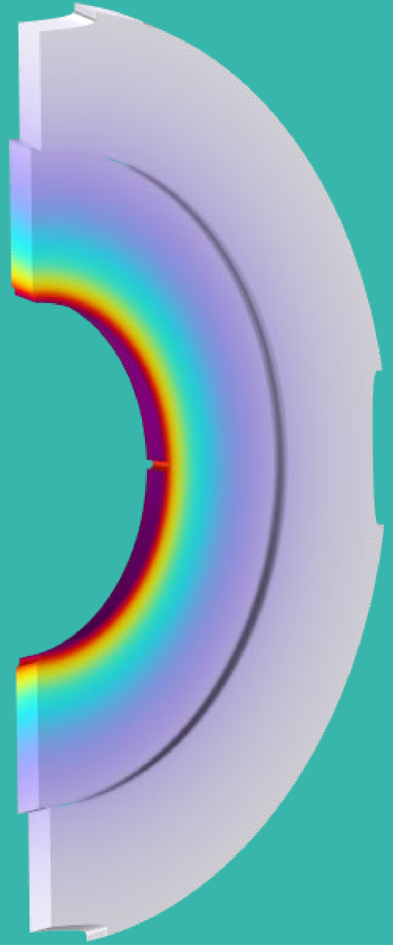


Radiation damage in a power dump

CHRIS SPRUIJTENBURG

(CHRIS.SPRUIJTENBURG@DEMCON.COM)

COMSOL CONFERENCE 2023

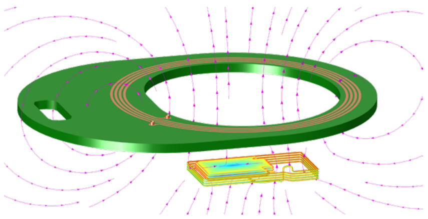
DEMCON | MULTIPHYSICS

Introduction

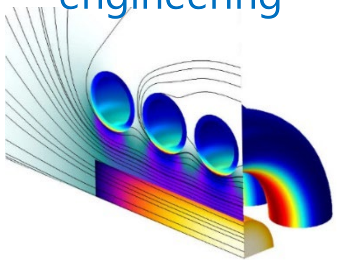
- Demcon group:
  - Engineering group, Netherlands
  - +1000 employees
  - Product and one-off development

- **Demcon Multiphysics**:
  - Physics consultancy division
  - 20 employees
  - Active in flow, thermal, electromagnetism, structural, etc.

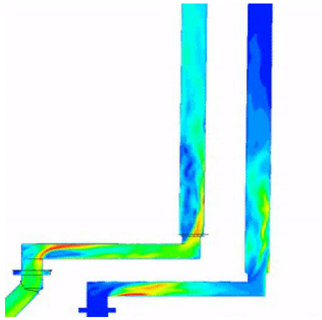
Electromagnetics



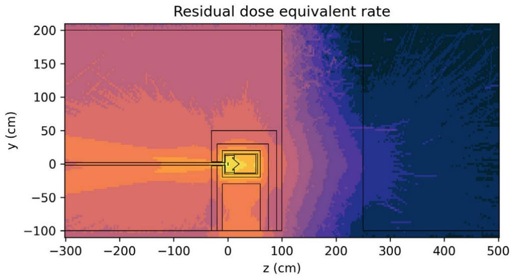
Thermal engineering



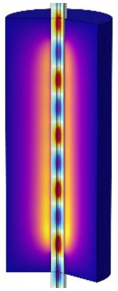
Fluid flows



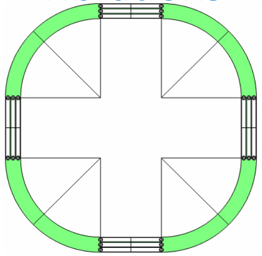
Nuclear physics



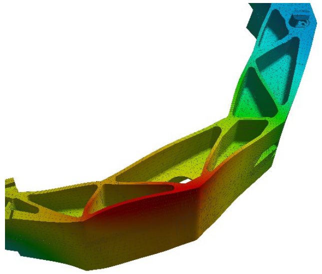
Plasma physics



Acoustics and vibrations



Structural mechanics



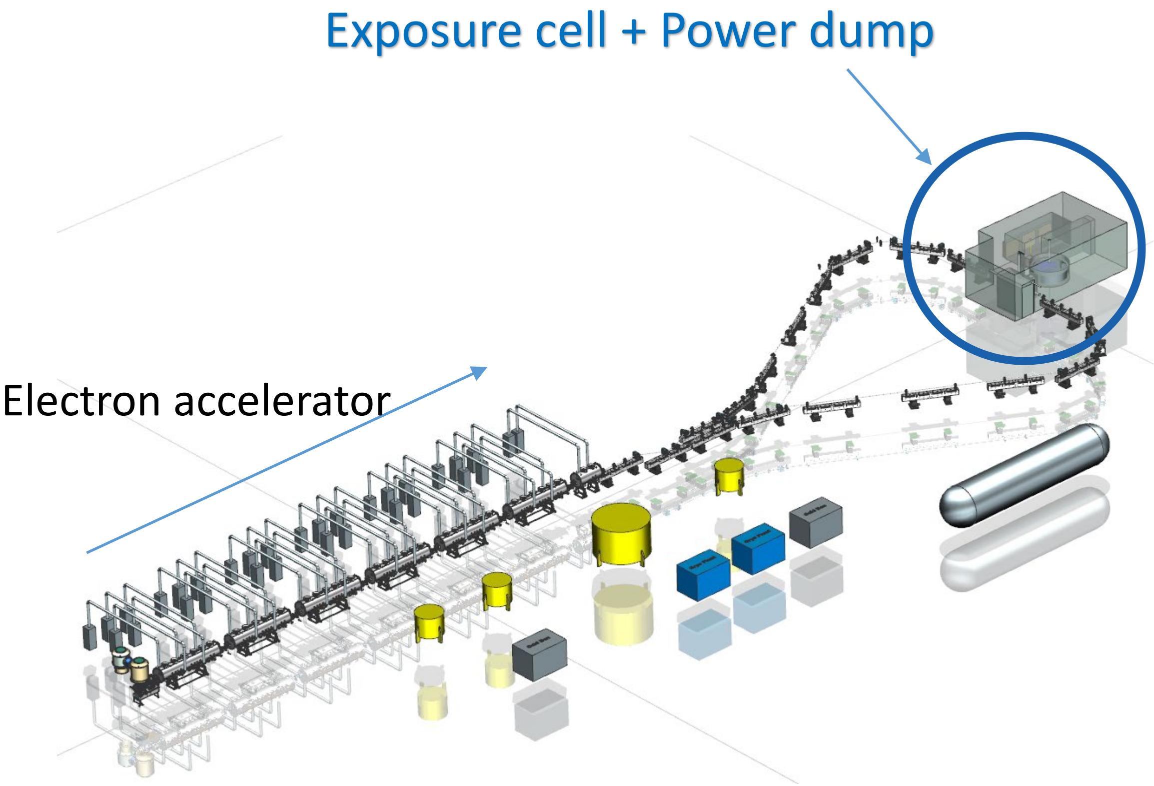
Experiments

Multiphysics engineer

Why a power dump?

- Medical isotope production through irradiation of a target
- Source
  - 75 MeV electrons
  - 3 MW power input
- Target: matchbox sized

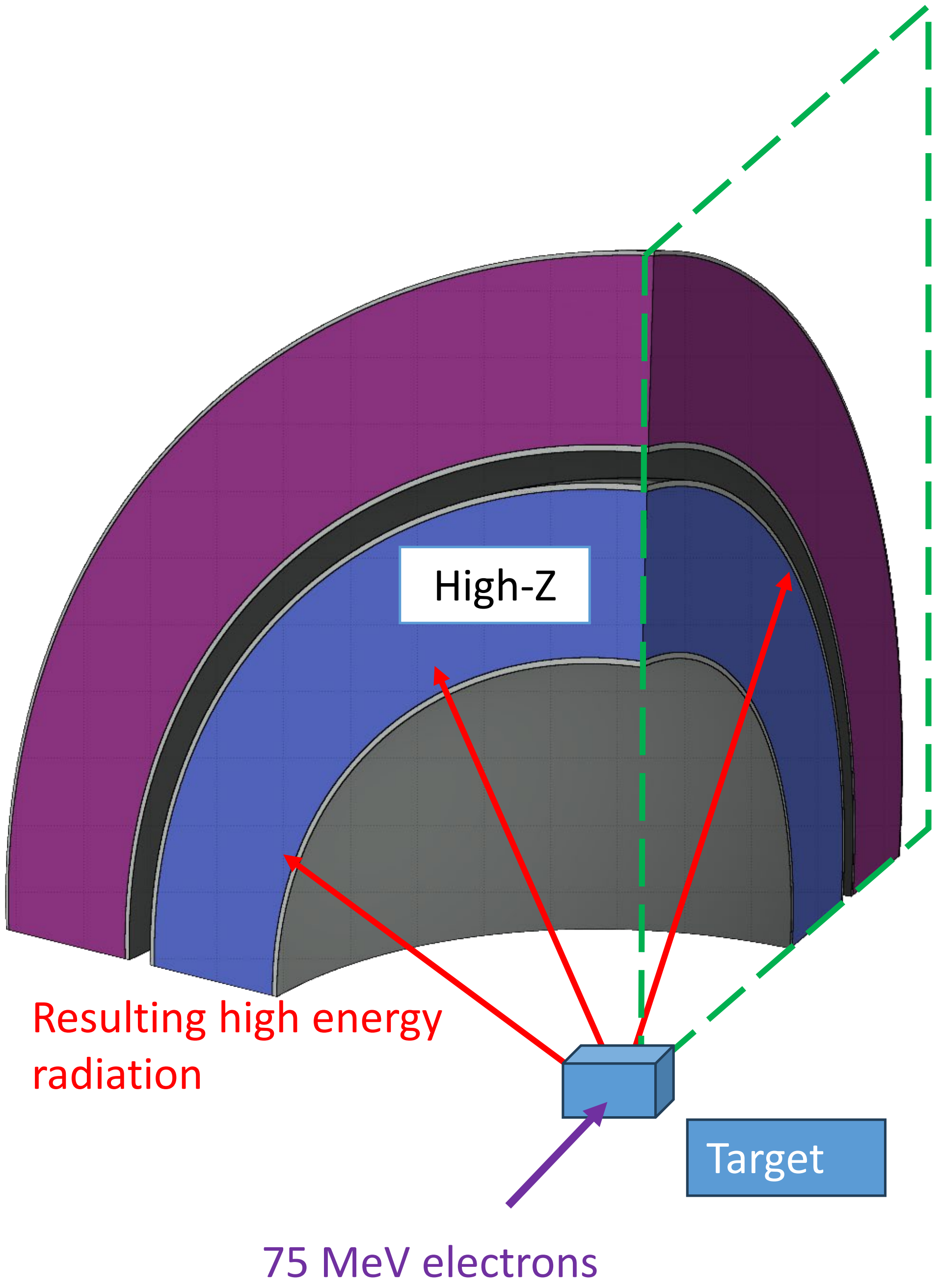
- A large amount of radiative power consisting of high energy photons need to be absorbed.
  - 2 MW in the target
  - 1 MW …somewhere else?



Power dump, overview

- A power dump was designed to absorb and divert this power (approx. 1 MW).
- A simplified octant of the geometry is shown on the right

- **Result**: Power dump is bombarded with high energy radiation, resulting from secondary radiation from the target.
- **Question**: Is the integrity of the power dump preserved after 30 years of continuous irradiation?



Questions to answer

- We need to answer the following questions:
  - What are the relevant radiological parameters for damage?
  - What is the subsequent swelling of the part?
  - Can the part survive according to the appropriate criteria?

Radiation damage - effects

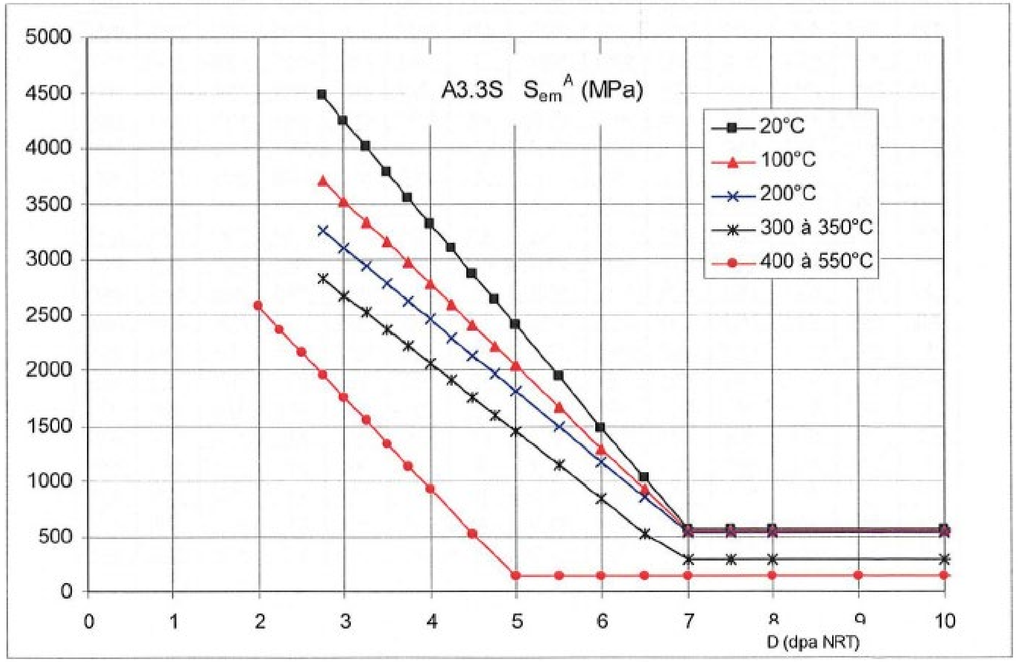
- The high energy radiation causes
  - Displacement damage
  - Production of gas in the form of He and H.

- Over time, additional stresses caused by **swelling**
- A change in properties due to **radiation hardening**
  - increased yield strength
  - reduced ductility

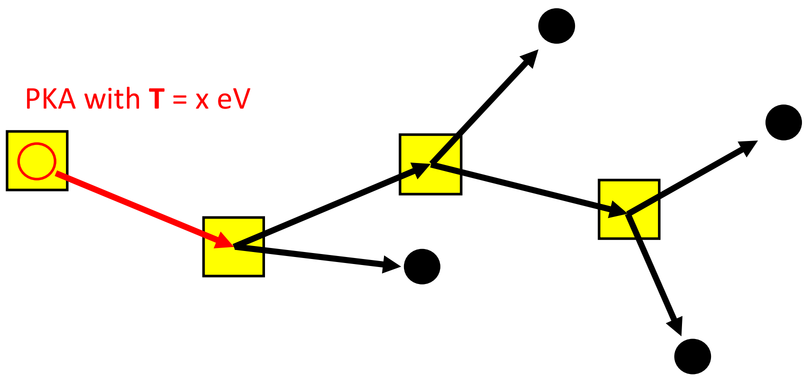
- All this can lead to failure. This risk needs to be assessed and potentially mitigated.

Allowable elastic membrane stress of 316 with irradiation (RCC-MRx)

Figure A3.3S.57: values of S_{em}^A, S_{em}^C, S_{em}^D and S_{et}^A, S_{et}^C, S_{et}^D (MPa) function of temperature θ (°C) and damage D (dpa NRT), when r=3



Physics of radiation damage



- In a radiation damage event, atoms are displaced from the crystal lattice in a cascade, set off by some "Primary knock-on atom" (PKA). This PKA carries a certain amount of kinetic energy **T**.
- The (energy dependent) PKA spectrum is correlated to certain damage morphologies.

1. Kai Nordlund, et.al.,Primary radiation damage: A review of current understanding and models, Journal of Nuclear Materials, Volume 512, **2018**
2. Li, S.-H.; Li, J.-T.; Han, W.-Z. Radiation-Induced Helium Bubbles in Metals. *Materials* **2019**, *12*, 1036.

Physics of radiation damage

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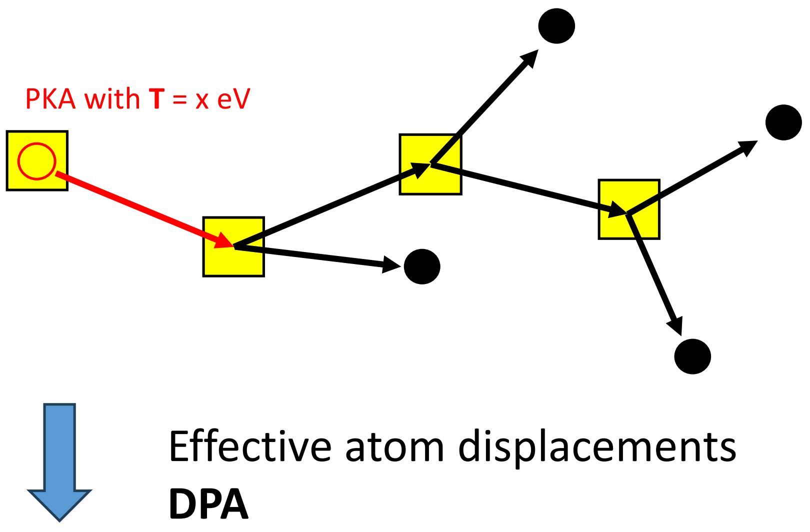
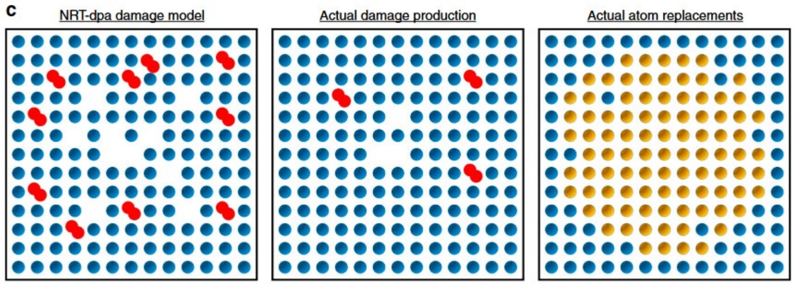
- The (energy dependent) PKA spectrum is correlated to certain damage morphologies.
- The damage metric of **Displacements per atom** (DPA) wraps up these microscopic considerations into a macroscopic parameter.



Effective atom displacements
DPA

1.



2.

1. Kai Nordlund, et.al.,Primary radiation damage: A review of current understanding and models, Journal of Nuclear Materials, Volume 512, **2018**
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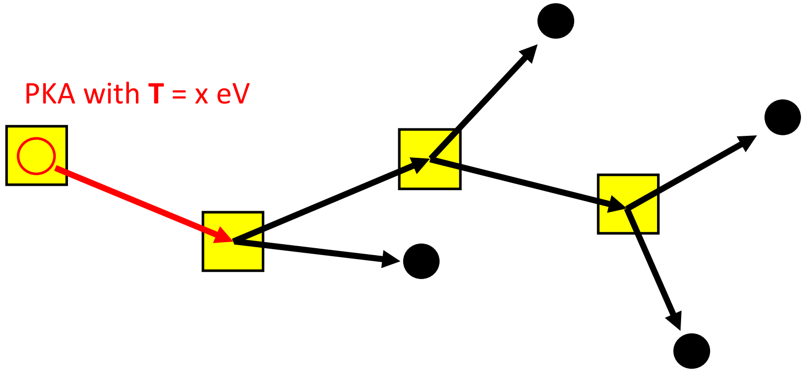
Physics of radiation damage

- In a radiation damage event, atoms are displaced from the crystal lattice in a cascade, set off by some “Primary knock-on atom” (PKA). This PKA carries a certain amount of kinetic energy **T**.
- The (energy dependent) PKA spectrum is correlated to certain damage morphologies.
- The damage metric of **Displacements per atom** (DPA) wraps up these microscopic considerations into a macroscopic parameter.
- How does swelling over time relate to DPA? → **Next slide**



Effective atom displacements
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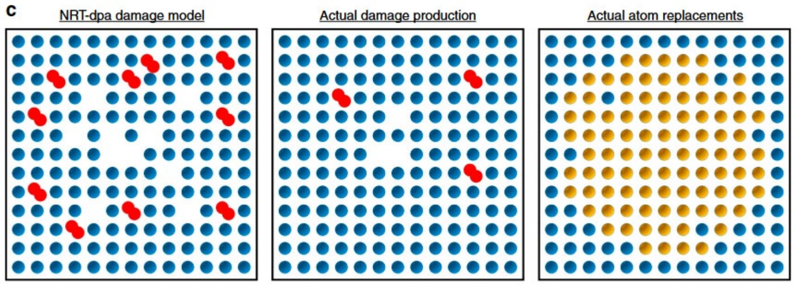
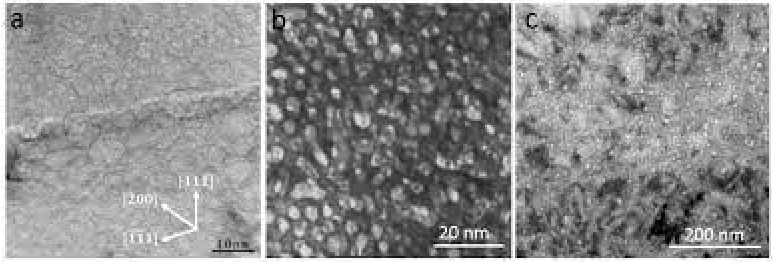
1.



Time (+ Gas production) = Swelling

2.



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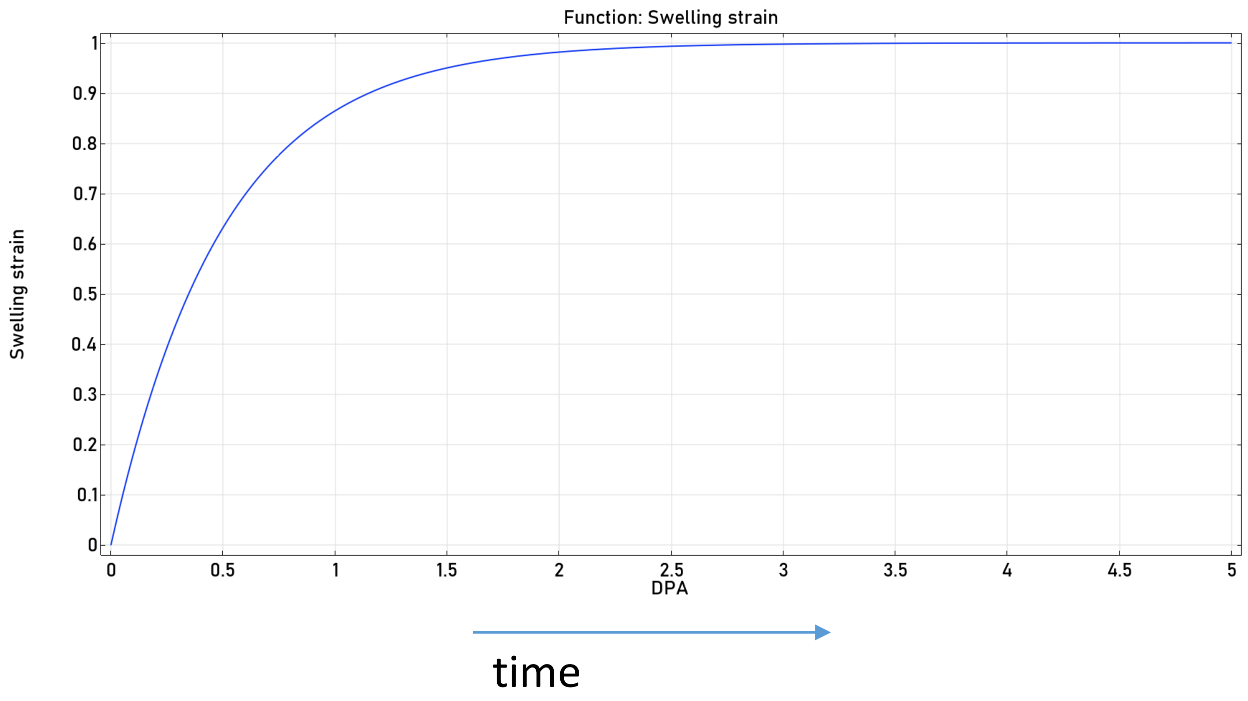
2. Li, S.-H.; Li, J.-T.; Han, W.-Z. Radiation-Induced Helium Bubbles in Metals. *Materials* **2019**, *12*, 1036.

Swelling relation



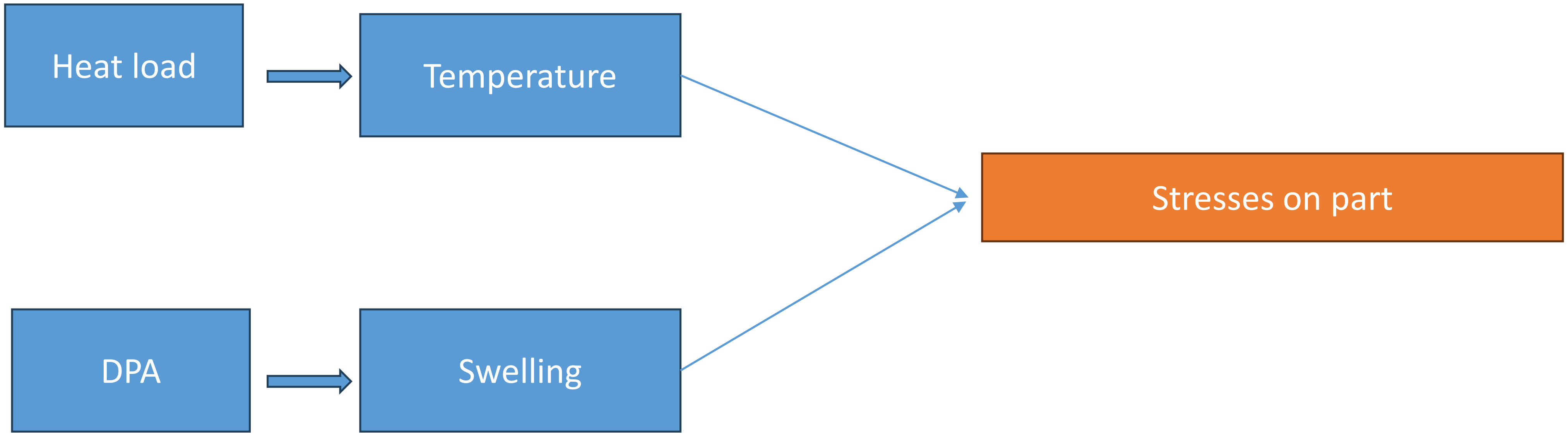
- It is expected that the swelling saturates after a certain amount of accumulated damage (DPA).
- We model this using the following relation.

$$\epsilon_{swell}(DPA) = \epsilon_{saturation} \cdot (1 - \exp(-2 \cdot \frac{DPA(t)}{DPA_{sat}})$$

Approach

Radiological parameters (FLUKA)

Mechanical (COMSOL)



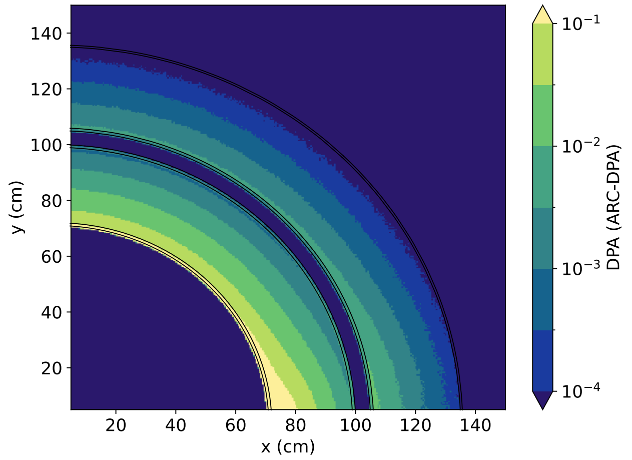
Calculating radiological parameters

- Monte-Carlo radiation transport using FLUKA:
  - Full irradiation profile, bias relevant interactions, such as photo-nuclear and neutron interactions.

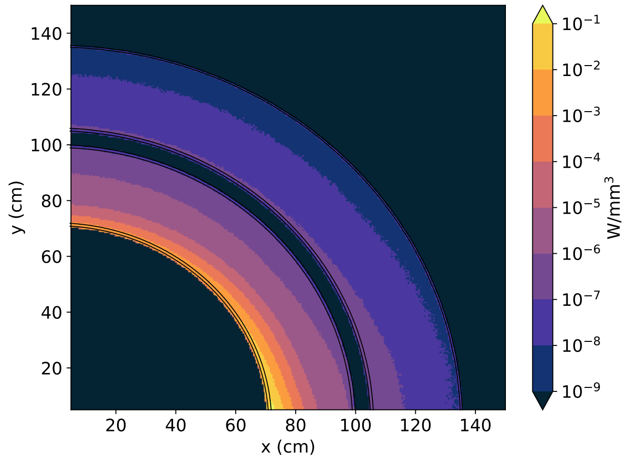
- FLUKA allows us to
  - directly capture DPA while also accounting for defect recombination.
  - Simulate the distribution of deposited energy in the form of heat. This heat load is necessary, as it causes thermal expansion (and stress) in the material.

- The results can be seen in the figures, showing a cylindrically symmetric simplified geometry of the right-half of the power dump. These results form the input for further structural analysis.

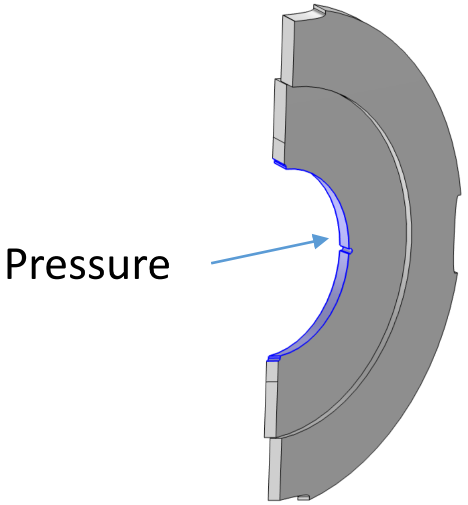
DPA

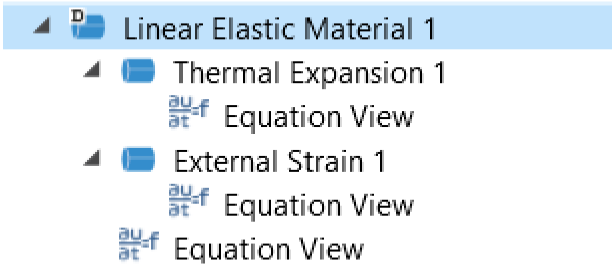


Heat load



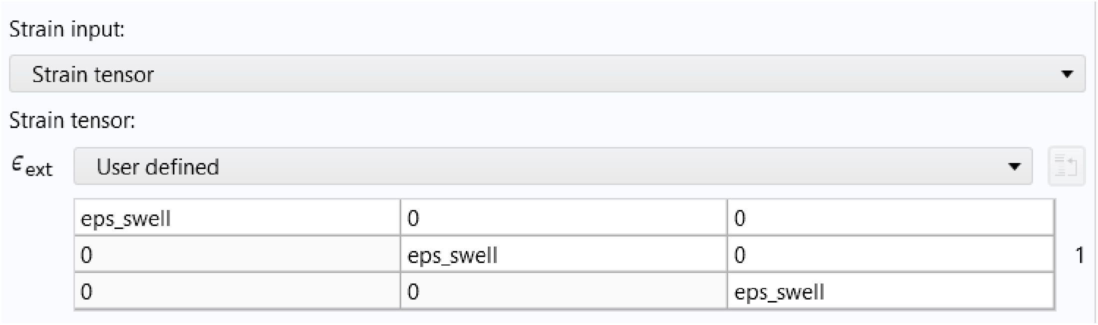
Boundary conditions in a nutshell





- Thermal expansion (Temperature)
- External strain (Swelling)
- Gravity
- Pressure boundary load (vacuum vessel)
- +structural mechanics (prescribed displacements)

$$\epsilon_{swell}(DPA) = \epsilon_{saturation} \cdot (1 - \exp(-2 \cdot \frac{DPA(t)}{DPA_{sat}})$$

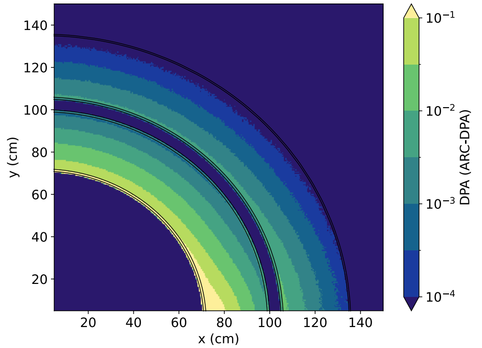


Import into COMSOL

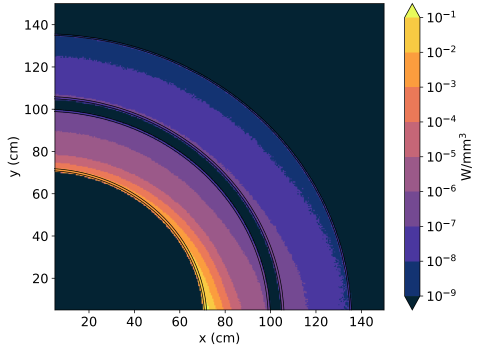
- Use COMSOL to directly import:
  - Part geometry
  - Relevant parameters calculated with FLUKA

- The spatial distribution of damage production (DPA/s) is used as an input to define a swelling strain that varies in space and time.

DPA

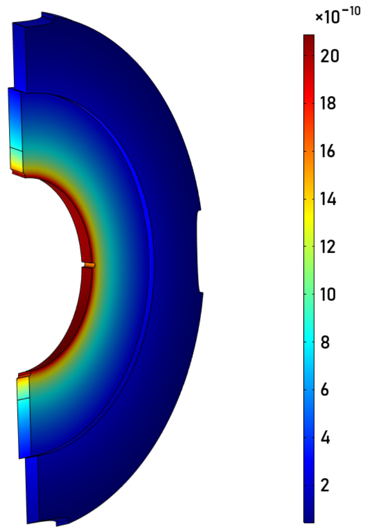


Heat load



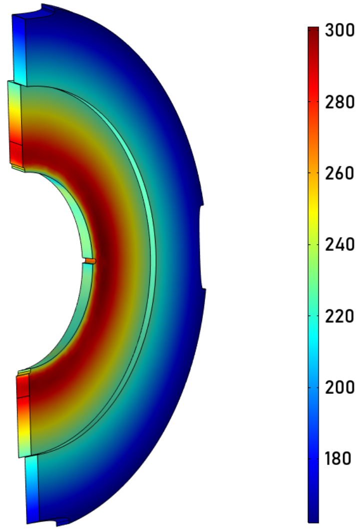
Swelling strain

tt=30 year, dpa_sat=0.3 Surface: Interpolation 2 (1/s)



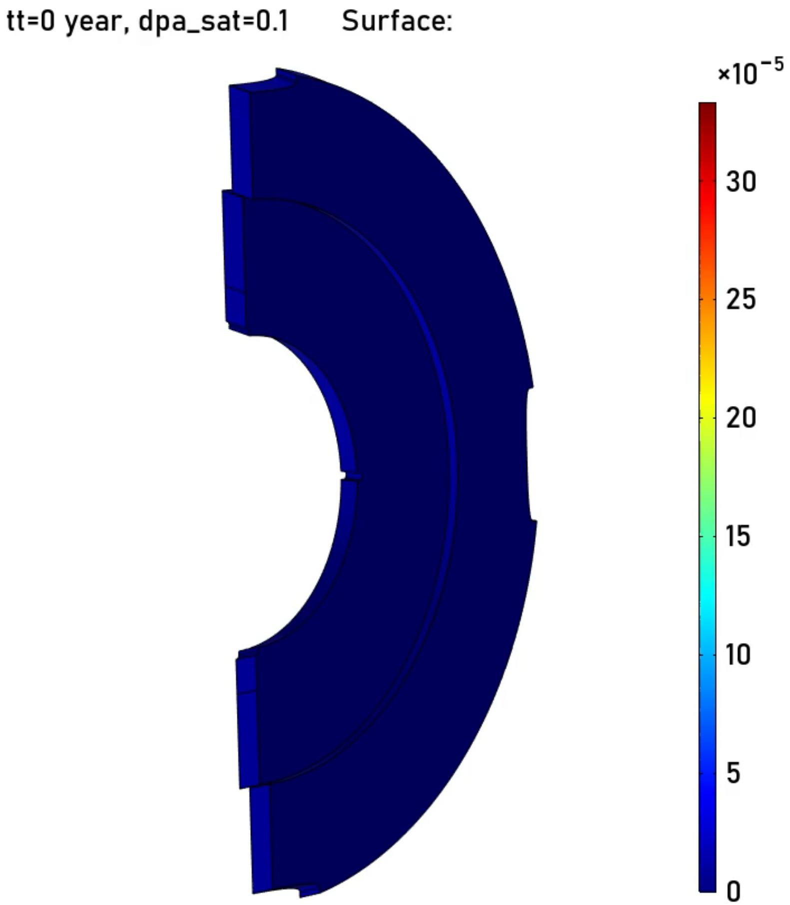
Temperature

tt=30 year, dpa_sat=0.3 Surface: Interpolation 1 (degC)



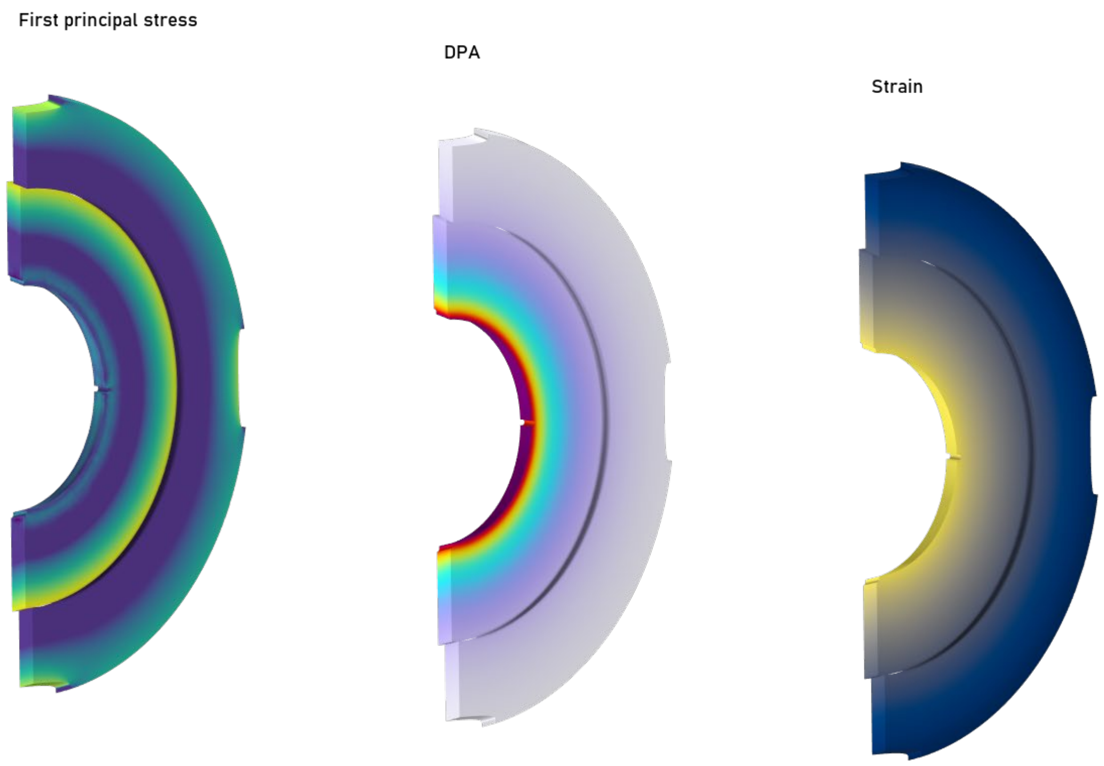
Swelling over time

- Shown is the swelling strain ϵ_{swell} over the lifetime of the part.
- Quick increase near the radial center.



Stress analysis – Summary

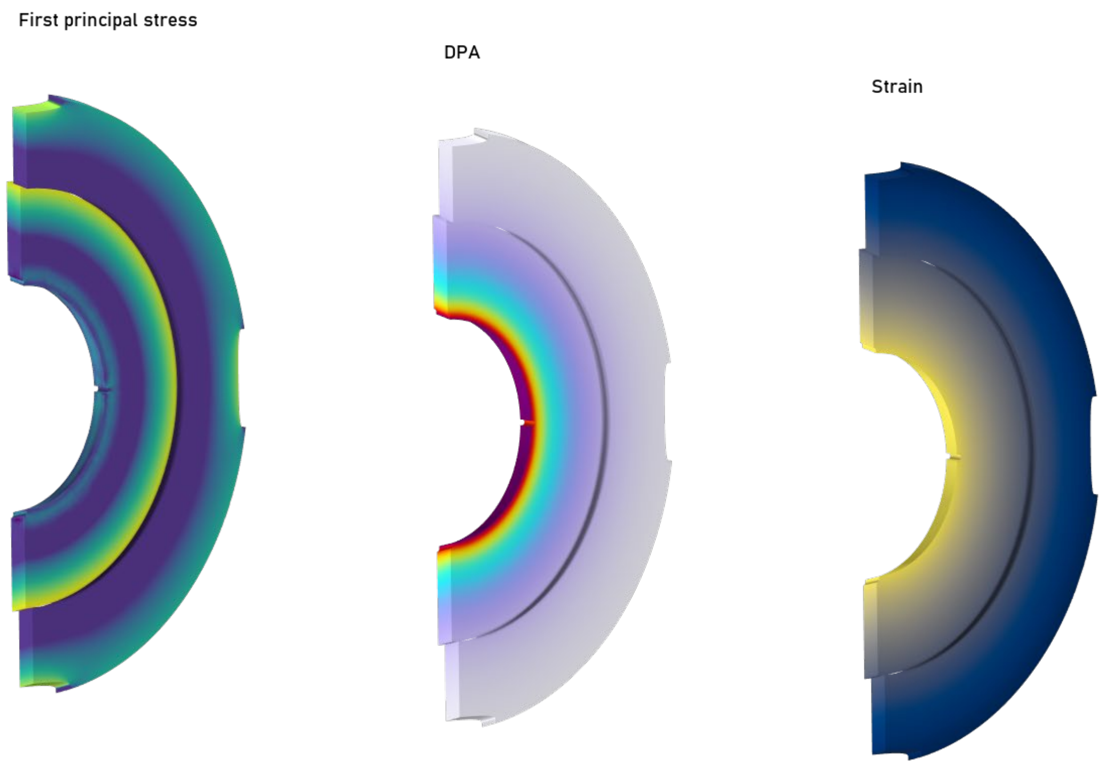
- **We need a conservative value for failure**
  - The part is brittle so fast-fracture will be the primary mode of failure. So it is appropriate to look at the first principal stress.
- The maximum expected crack size is much smaller than the part. A simple analytical relation can be used.
- Using the material fracture toughness K_1=5 [MPa$\sqrt{m}$]
  - Critical value of: **250 MPa.**
- A maximum of **115 MPa** is found over the lifetime. The part thus survives using a conversative estimations.



Impact

- We can make predictions on the impact of radiation damage and directly couple radiation quantities (such as heat load and DPA) to structural quantities. Failure modes can thus be evaluated and assessed.
- Analysis is also possible for materials which are ductile instead of brittle. This only requires looking at criteria other than fast fracture.
- Further analysis and comparison to design and construction codes for nuclear components (RCC-MRx) is now possible, and will allow adherence to the highest standards in this field.

- Contact: chris.spruijtenburg@demcon.com



Questions?

Multiphysics engineers

- Come find us at our other talks or at the posters

- Degassing of PP pellets in a silo - Rien Wesselink
  - **Oct 26, 08:30** - Chemical Reaction Engineering and Transport
- Magnetic shielding of an electrical substation - Sybrand Zeinstra
  - **Oct 26, 08:30** - Low-Frequency Electromagnetics II
- Modelling of high-temperature superconductors - Koen de Mare
  - **Oct 25, 17:00** - Low-Frequency Electromagnetics II
- Radiation damage in a power dump - Chris Spruijtenburg
  - **Oct 25, 15:30** - Structural Mechanics

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Contact: chris.spruijtenburg@demcon.com

Full relation criteria

- Since the crack dimensions are much smaller than the height and the width of the tungsten disks (100 um <<< 1 cm) we can use the following formula
  - $K_1 = \sigma\sqrt{\pi a} * 1.122$ where σ is the tensile stress and a the crack size

- With K_1 = 5 MPam$^{1/2}$ and a = 100 um this leads to a maximal allowable 1st principal stress of 250 Mpa.

RCC-MRx

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A3.3S.25 SPECIFIC HEAT CAPACITY, THERMAL CONDUCTIVITY, THERMAL DIFFUSIVITY

The specific heat capacity C_p, the thermal conductivity λ and the thermal diffusivity a are given as a function of temperature θ by the **formula A3.3S.25** and the **table A3.3S.25**.

- **Formula A3.3S.25** :
  $C_p = 462.69 + 0.52026.\theta - 1.7117\ 10^{-3}\ \theta^2 + 3.3658\ 10^{-6}\ \theta^3 - 2.1958\ 10^{-9}\ \theta^4$
  $\lambda = 13.98 + 1.502\ 10^{-2}\ \theta$
  $a = \lambda/(\rho.C_p)$
  In these formula, C_p is expressed in J / (kg.K), λ in W / (m.K), a in m^2 / s and θ in °C.
  This formula is valid for $20 \leq \theta\ °C \leq 800$

Table A3.3S.25: specific heat capacity C_p, thermal conductivity λ, thermal diffusivity a

θ (°C)	20	50	100	150	200	250	300	350	400
C_p (J/kg.K)	472	485	501	512	522	530	538	546	556
λ (W/m.K)	14.28	14.73	15.48	16.23	16.98	17.74	18.49	19.24	19.99
a ($10^{-6}m^2$/s)	3.81	3.84	3.91	4.02	4.14	4.27	4.40	4.52	4.63

θ (°C)	450	500	550	600	650	700	750	800
C_p (J/kg.K)	567	578	590	601	610	615	615	607
λ (W/m.K)	20.74	21.49	22.24	22.99	23.74	24.49	25.25	26.00
a ($10^{-6}m^2$/s)	4.72	4.81	4.89	4.98	5.09	5.22	5.39	5.65

eurofer

A3.19AS.25 SPECIFIC HEAT CAPACITY, THERMAL CONDUCTIVITY, THERMAL DIFFUSIVITY

The specific heat capacity C_p, the thermal conductivity λ and the thermal diffusivity a are given as a function of temperature θ by the **formula A3.19AS.25** and the **table A3.19AS.25**.

- **Formula A3.19AS.25** :
  $C_p = 421.5 + 0.93876\ \theta - 2.972 \times 10^{-3}\ \theta^2 + 4.098 \times 10^{-6}\ \theta^3$
  $\lambda = 27.403 + 0.0353\ \theta - 1.289.10^{-4}\ \theta^2 + 1.3398.10^{-7}\ \theta^3$
  $a = \lambda / (\rho.C_p)$
  In these formulae, C_p is expressed in J / (kg.K), λ in W / (m.K), a in m^2 / s and θ in °C.
  These formulae are valid for $20 \leq \theta\ °C \leq 600$

Table A3.19AS.25: specific heat capacity C_p, thermal conductivity λ, thermal diffusivity a

θ (°C)	20	50	100	150	200	250	300
λ (W/m.K)	27.63	28.73	29.87	30.32	30.28	29.95	29.51
C_p (J/kg.K)	439	462	490	509	523	534	546

θ (°C)	350	400	450	500	550	600
λ (W/m.K)	29.10	28.84	28.82	29.08	29.62	30.38
C_p (J/kg.K)	562	584	616	660	721	800

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A3.3S.32 NEGLIGIBLE IRRADIATION CURVE

Negligible irradiation damages D_{ineg} are expressed in the **table A3.3S.32** as a function of temperature θ.
Irradiation damage is expressed using the displacements per atoms (dpa) NRT as defined by M.J. Norgett, M.T. Robinson and I.M. Torrens.

A3.3S.33 MAXIMUM ALLOWABLE IRRADIATION

Maximum allowable irradiation damages D_{imax} are expressed in the **table A3.3S.32** as a function of temperature θ.

Table A3.3S.32: negligible and maximum allowable irradiation damages

θ (°C)	20°C to 375°C	375°C to 400°C	400°C to 425°C	425°C to 550°C
D_{ineg} (dpa)	2.75	2.6	2	2
D_{imax} (dpa)	53	40	30	24

The negligible criterion indicates the lowest /known/ DPA for which no discernable effects are expected

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A3.19AS.3 BORDER LINES

A3.19AS.31 NEGLIGIBLE CREEP AND THERMAL AGEING CURVES

A3.19AS.311 NEGLIGIBLE CREEP CURVE

For temperatures less than 375°C, creep is negligible whatever the holding time.

A3.19AS.312 NEGLIGIBLE THERMAL AGEING CURVE (NOT PROVIDED)

A3.19AS.32 NEGLIGIBLE IRRADIATION CURVE

Negligible irradiation damages D_{ineg}, for an irradiation temperature of 300°C, are expressed in **table A3.19AS.32** as a function of operating temperature θ.
Irradiation damage is expressed using the displacements per atoms (dpa) NRT as defined by M.J. Norgett, M.T. Robinson and I.M. Torrens.

A3.19AS.33 MAXIMUM ALLOWABLE IRRADIATION

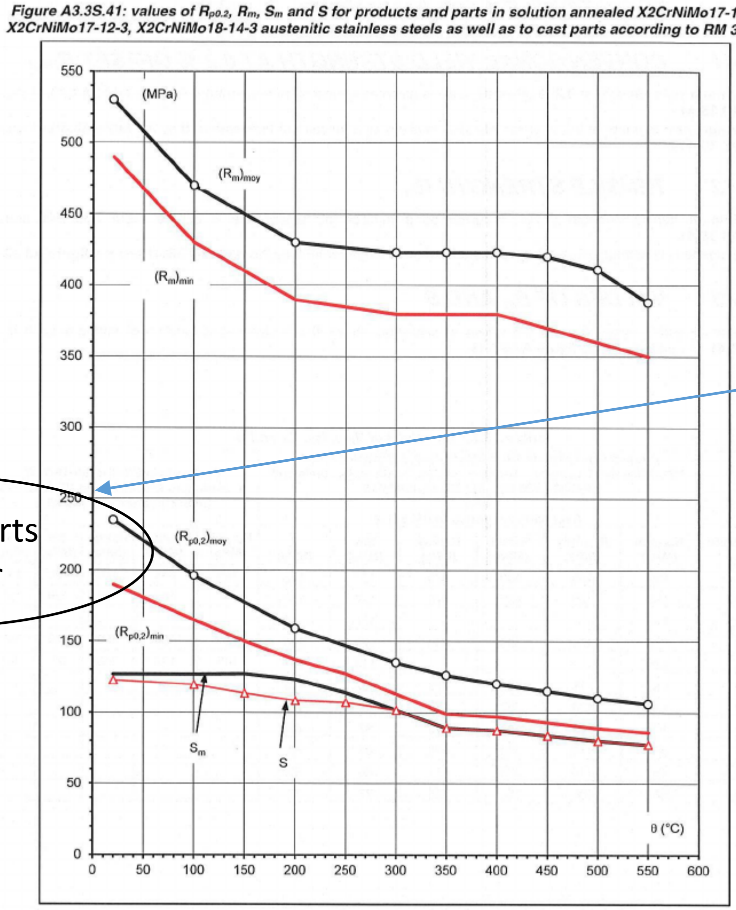
Maximum allowable irradiation damages D_{imax}, for an irradiation temperature of 300°C, are expressed in the **table A3.1S.32** as a function of operating temperature θ.

Table A3.19AS.32: negligible and maximum allowable irradiation damages

θ (°C)	20°C	100°C	200°C	300 °C
D_{ineg} (dpa)	0.3	0.3	0.3	0.3
D_{imax} (dpa)	0.3	2.3	6.8	13.3

Yield strength (before irradiation)

316



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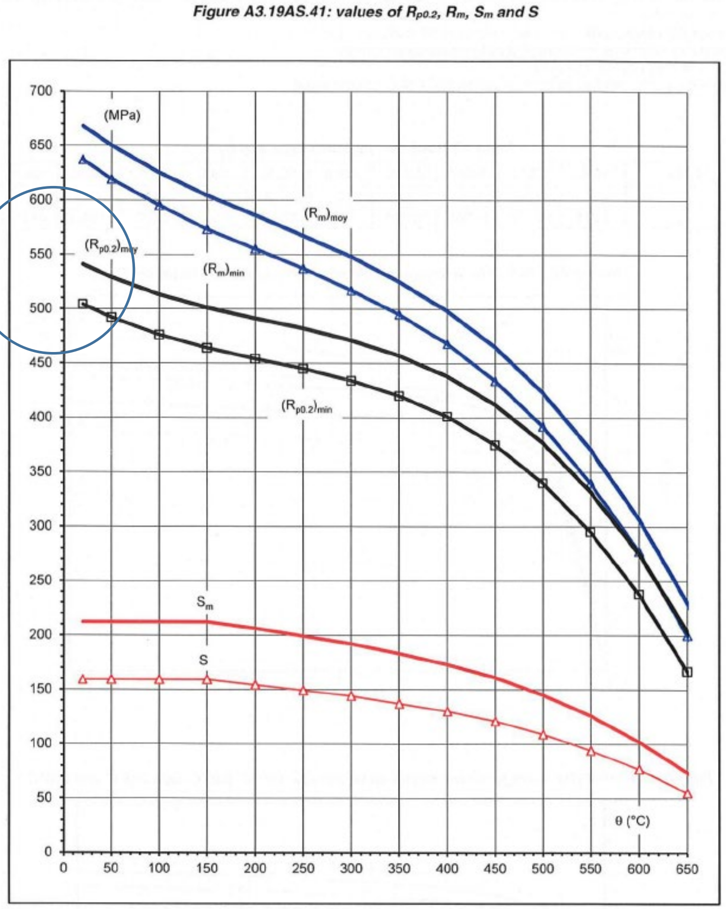


Rp0.2%, Starts out lower

316

A3.3S.6 PROPERTIES FOR ANALYSIS - IRRADIATION

Irradiation damage is expressed using the displacements per atoms (dpa) NRT as defined by M.J. Norgett, M.T. Robinson and I.M. Torrens.

A3.3S.61 CONVENTIONAL YIELD STRENGTH AT 0.2 % OFFSET $R_{P0.2}$ (after irradiation)

For irradiation with a damage D equal or less than 0.5 dpa, the conventional yield strength at 0.2% offset $R_{p0.2}$ before irradiation **(A3.3S.41)** are applicable.
For a damage D greater than 0.5dpa, the conventional yield strengths at 0.2% offset $R_{p0.2}$ increase linearly with the damage D until saturated values function of the temperature as given in **Table A3.3S.61**.

A3.3S.62 TENSILE STRENGTH R_m (after irradiation)

For irradiation with a damage D equal or less than 0.5 dpa, the tensile strength R_m before irradiation **(A3.3S.42)** are applicable.
For a damage D greater than 0.5dpa, the tensile strengths R_m increase linearly with the damage D until saturated values function of the temperature as given in **Table A3.3S.61**.

Table A3.3S.61: saturated values of $R_{p0.2}$ and R_m after irradiation

θ (°C)	20	250	300	350	400	450	550
D (dpa)	7	7	7	7	12	15	15
$(R_{p0.2})_{min}$ (MPa)	660	660	765	700	600	340	
$(R_{p0.2})_{moy}$ (MPa)	737	737	852	783	672		
$(R_m)_{min}$ (MPa)	680	680	780	735	665	400	350
$(R_m)_{moy}$ (MPa)	760	760	870	821	742		

A3.3S.63 VALUES OF S_{em} AND S_{et} (after irradiation)

For level A, C and D criteria, the allowable elastic membrane stresses S_{em}^A, S_{em}^C, S_{em}^D and the allowable elastic total stresses S_{et}^A, S_{et}^C, S_{et}^D are given by the **table A3.3S.63** and the **figure A3.3S.63** as a function of the temperature θ (°C) and the damage D in dpa NRT, in case the elastic follow-up on secondary stress r is equal to 3 **(RB 3225)**.
For this material: $S_e^A = (2 / 2.5)\ S_e^C = (1.35 / 2.5)\ .S_e^D$
In case r is not equal to 3, formulae are proposed in **A3.GEN.42.**
Unless a smaller value can be justified, r = 3 shall be used for structures other than pipes and branches.
For pipes, this elastic follow-up factor may be calculated using the method described in **RB 3643.31**.
For branches, unless a smaller value can be justified, r = 8 shall be used.

eurofer

A3.19AS.6 PROPERTIES FOR ANALYSIS – IRRADIATION

Irradiation damage D is expressed using the displacements per atoms (dpa) NRT as defined by M.J. Norgett, M.T. Robinson and I.M. Torrens.

A3.19AS.61 CONVENTIONAL YIELD STRENGTH AT 0.2 % OFFSET $R_{P0.2}$ (after irradiation)

The minimum conventional yield strength at 0.2% offset $(R_{p0.2})_{min}$ at 300°C is given as a function of damage D (dpa) in **table A3.19AS.61**.

A3.19AS.62 TENSILE STRENGTH R_m (after irradiation)

The minimum tensile strength $(R_m)_{min}$ at 300°C is given as a function of damage D (dpa) in **table A3.19AS.61**.

Table A3.19AS.61: minimum values of $R_{p0.2}$ and R_m at 300°C as a function of damage D (dpa NRT)

θ (°C)	D (dpa)	$(R_{p0,2})_{min}$ (MPa)	$(R_m)_{min}$ (MPa)
300	0	434	517
300	0.3	537	620
300	0.5	566	649
300	0.8	599	683
300	1	618	701
300	2	685	769
300	5	796	880
300	10	879	963
300	13.3	906	990

A3.19AS.63 VALUES OF S_{em} AND S_{et} (after irradiation)

For level A, C and D criteria, the allowable elastic membrane stresses S_{em}^A, S_{em}^C, S_{em}^D and the allowable elastic total stresses S_{et}^A, S_{et}^C, S_{et}^D are given by the **table A3.19AS.63** and the **figure A3.19AS.63** as a function of the temperature θ (°C) and the damage D in dpa NRT, in case the elastic follow-up on secondary stress r is equal to 3 **(RB 3225)**.

In case r is not equal to 3, formulae are proposed in **A3.GEN.42**.
Unless a smaller value can be justified, r = 3 shall be used for structures other than pipes and branches.
For pipes, this elastic follow-up factor may be calculated using the method described in **RB 3643.31**.
For branches, unless a smaller value can be justified, r = 8 shall be used.

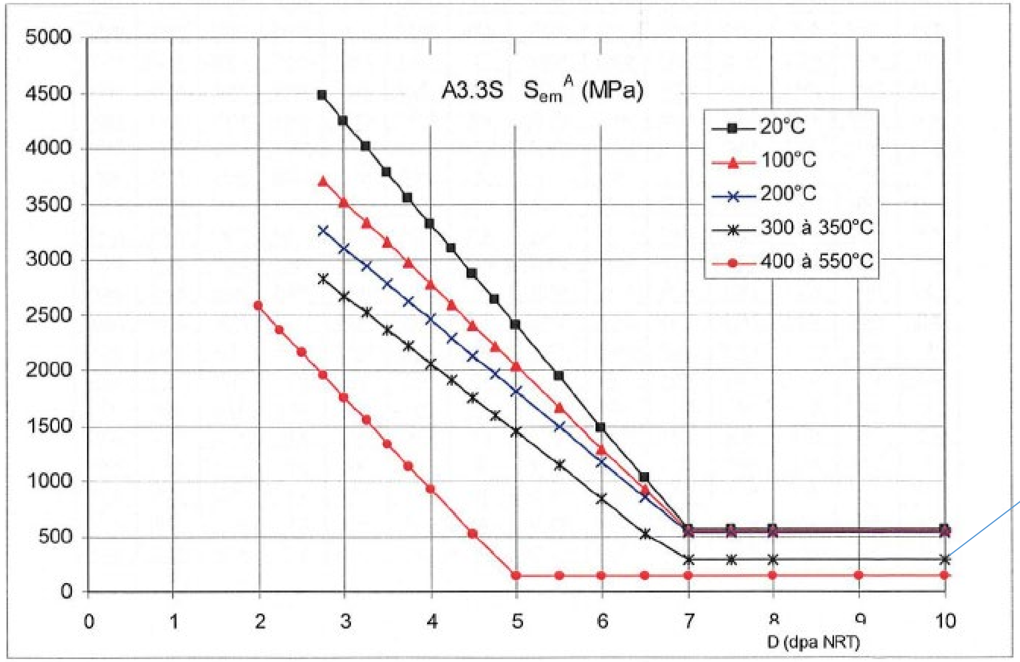
Table A3.19AS.63: values of S_{em}^A, S_{em}^C, S_{em}^D and S_{et}^A, S_{et}^C, S_{et}^D (MPa) at 300°C as a function of damage D (dpa NRT), when r=3

300°C

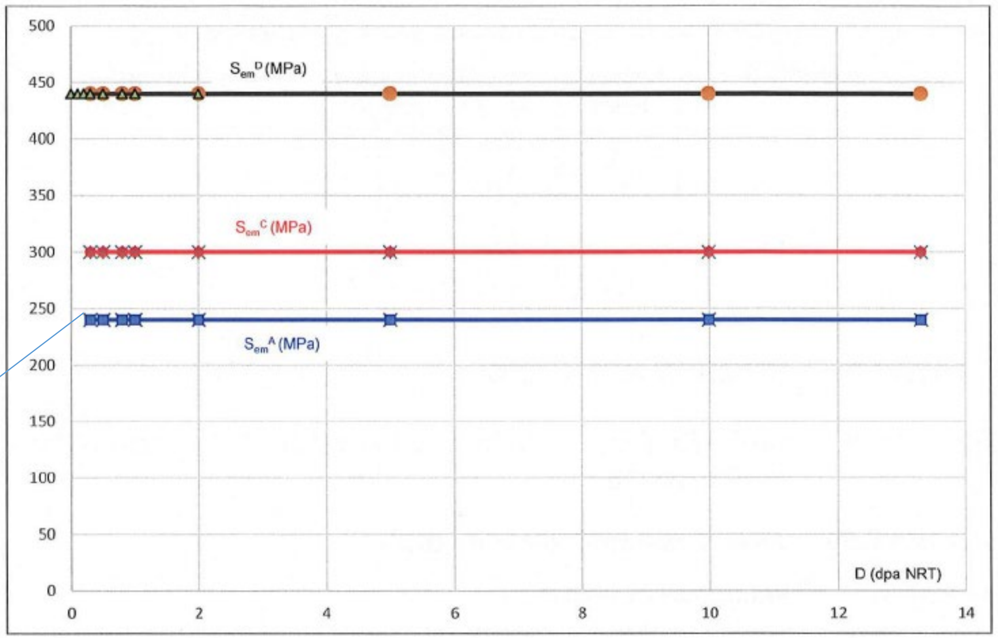
Maximum allowable stress

316

Figure A3.3S.57: values of S_{em}^A, S_{em}^C, S_{em}^D and S_{et}^A, S_{et}^C, S_{et}^D (MPa) function of temperature θ (°C) and damage D (dpa NRT), when r=3

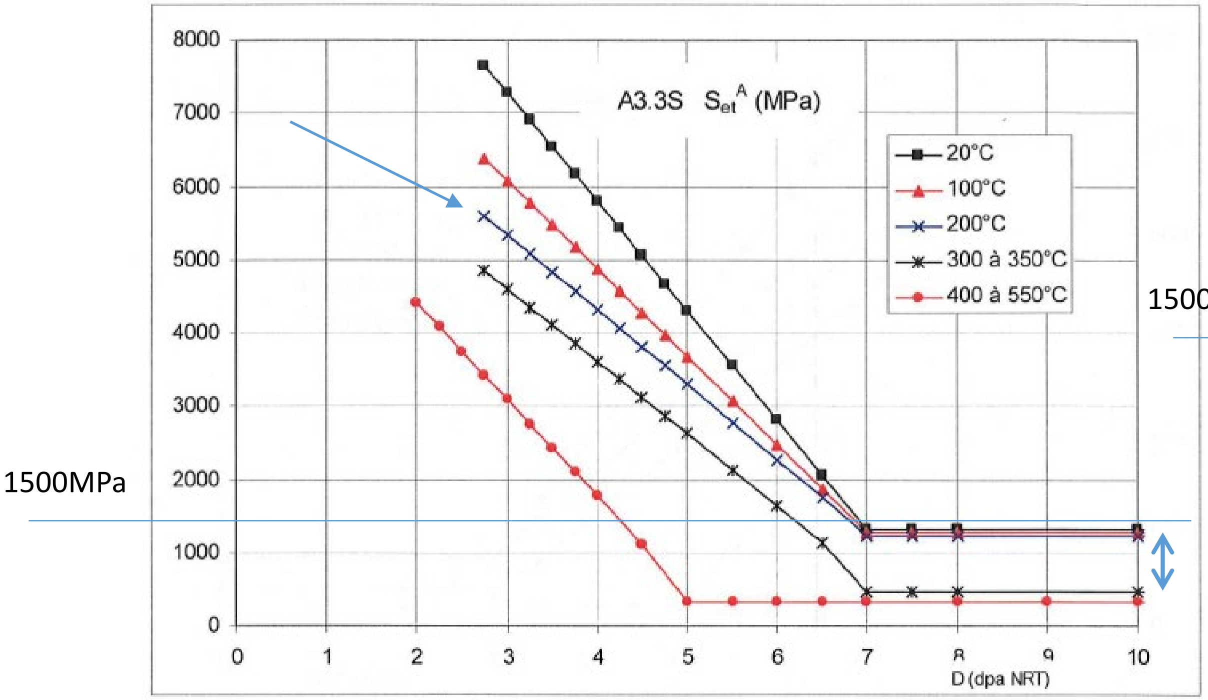


Eurofer (300C)

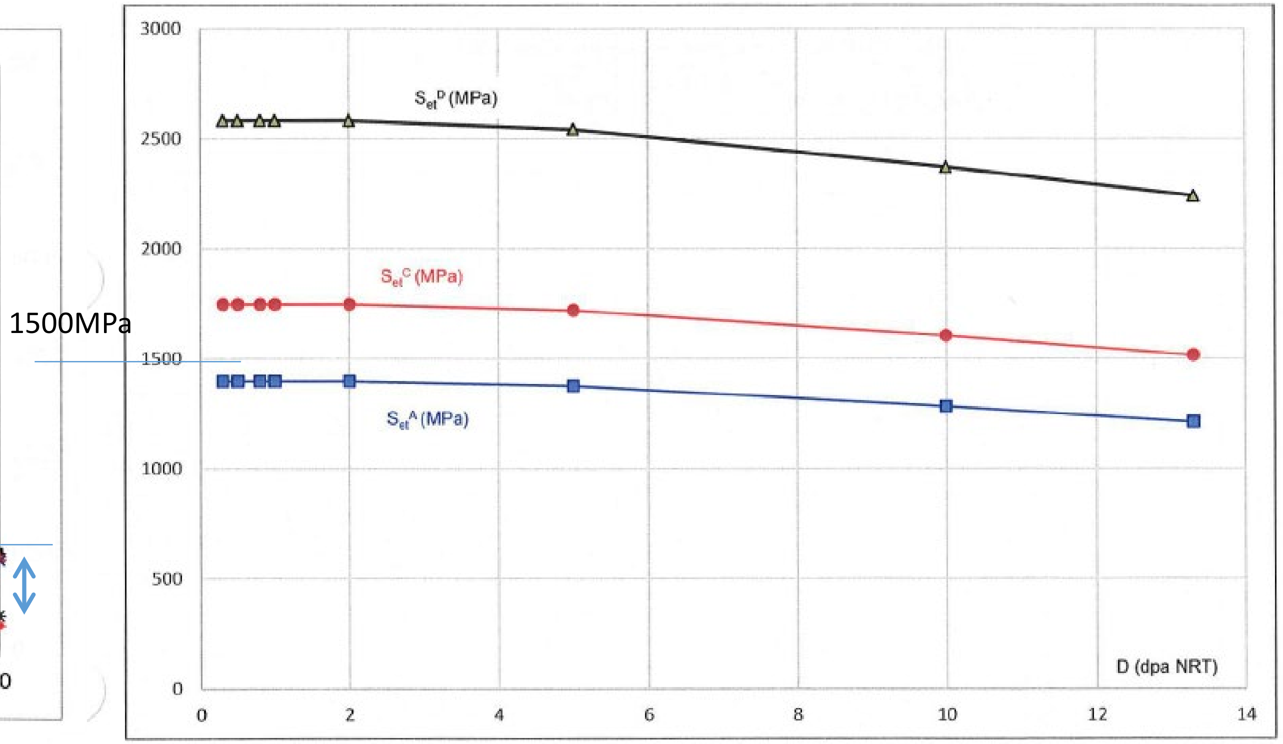


Maximum allowable stress

316



Eurofer (300C)



Going to 200C for 316 brings values close to eurofer

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300 to 350°C						
D	S_{em}^A	S_{em}^C	S_{em}^D	S_{et}^A	S_{et}^C	S_{et}^D
2.75	2827	3534	5235	4849	6062	8980
3	2674	3342	4951	4602	5753	8523
3.25	2520	3151	4668	4355	5444	8066
3.5	2367	2959	4384	4108	5136	7608
3.75	2214	2767	4100	3861	4827	7151
4	2060	2576	3816	3614	4518	6693
4.25	1907	2384	3532	3367	4209	6236
4.5	1754	2192	3248	3120	3900	5778
4.75	1600	2001	2964	2873	3592	5321
5	1447	1809	2680	2626	3282	4863
5.5	1140	1426	2112	2131	2664	3946
6	834	1042	1544	1634	2043	3026
6.5	527	659	976	1128	1410	2088
7	294	368	544	472	590	874
7.5	294	368	544	472	590	874
8	294	368	544	472	590	874
10	294	368	544	472	590	874
20	294	368	544	472	590	874
53	294	368	544	472	590	874

Table A3.19AS.63: values of S_{em}^A, S_{em}^C, S_{em}^D and S_{et}^A, S_{et}^C, S_{et}^D (MPa) at 300°C as a function of damage D (dpa NRT), when r=3

300°C						
D	S_{em}^A	S_{em}^C	S_{em}^D	S_{et}^A	S_{et}^C	S_{et}^D
0.3	240	300	440	1395	1744	2582
0.5	240	300	440	1395	1744	2582
0.8	240	300	440	1395	1744	2582
1	240	300	440	1395	1744	2582
2	240	300	440	1395	1744	2582
5	240	300	440	1374	1717	2542
10	240	300	440	1281	1601	2370
13.3	240	300	440	1211	1513	2240

For 10 DPA, S_{et} is ~3x higher for eurofer