Creep Of Steel P92 In Stagnant Lead And Air At 650°C

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Outline

- 9%-Cr f/m steel as a candidate for application in next generation of nuclear reactors
- Creep-to-rupture equipment for HLM
- Results:
  - Creep-to-rupture tests in air and Pb at 650°C
  - Post-exposure study of P92 tested in Pb and air
- Conclusion, Outlook

9%-Cr f/m steel as a candidate for application in next generation of nuclear reactors

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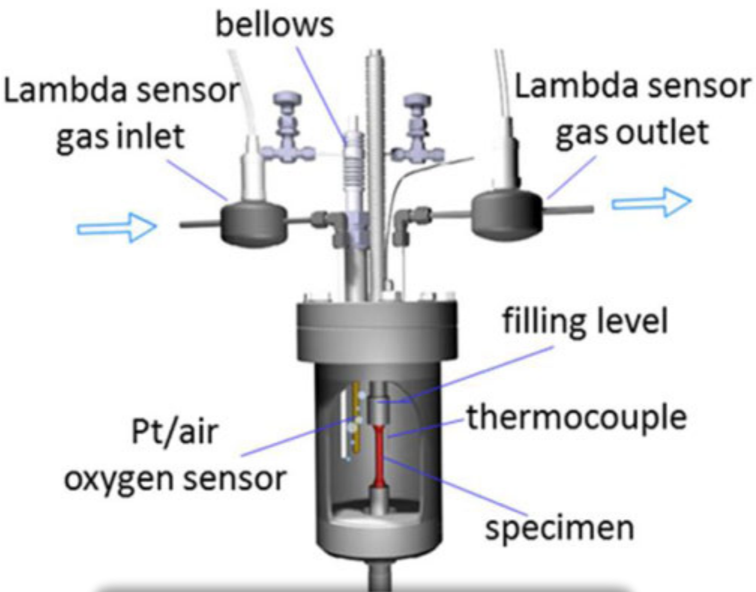
T91													
Fe	Cr	Mo	Mn	Si	V	Ni	Nb	Cu	Al	C	N	P	S
bal	8.99	0.89	0.38	0.22	0.21	0.11	0.06	0.06	.0146	.1025	.0442	.021	.0004
HT: normalising at 1050°C and tempering at 770°C													

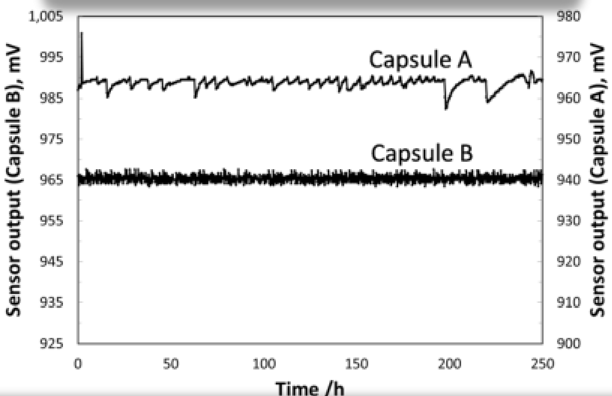
P92 = NF616														
Fe	Cr	Mo	W	Mn	Si	V	Ni	Nb	Al	C	N	P	S	B
bal	8.99	0.49	1.75	0.43	0.26	0.2	0.12	0.06	.016	0.11	.043	.018	.003	.002
HT: normalising at 1050°C and tempering at 770°C														

- **Increase of creep strength in P92 is reached due to W additions and decrease of Mo-content in comparison to T91.**

Creep-to-rupture equipment for HLM



EMF-run during tests



$c_o = 10^{-6}$ mass.-% at 650°C → U=965 mV

Displacement transducer outside the capsule

- ✓ Five capsules with liquid lead (900 ml)
- ✓ Three capsules with air (230 ml) for reference tests

Creep-to-rupture tests in air at 650°C

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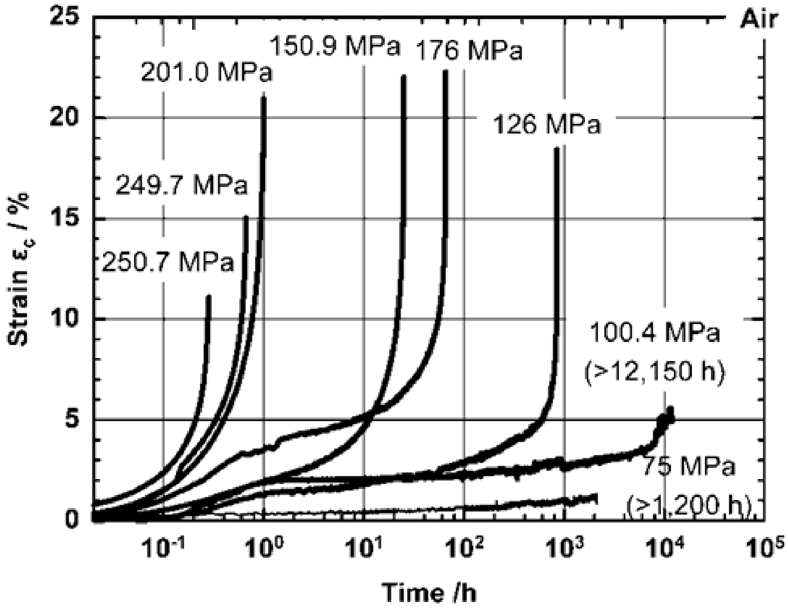
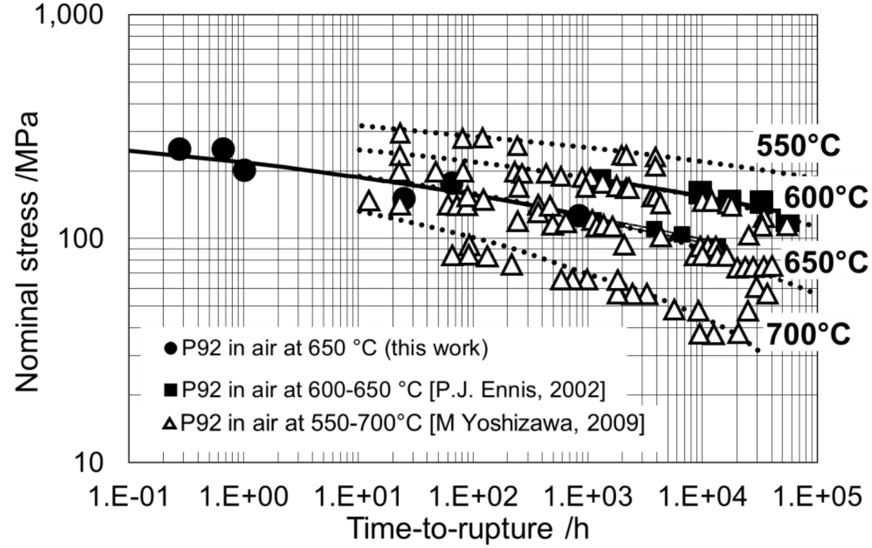
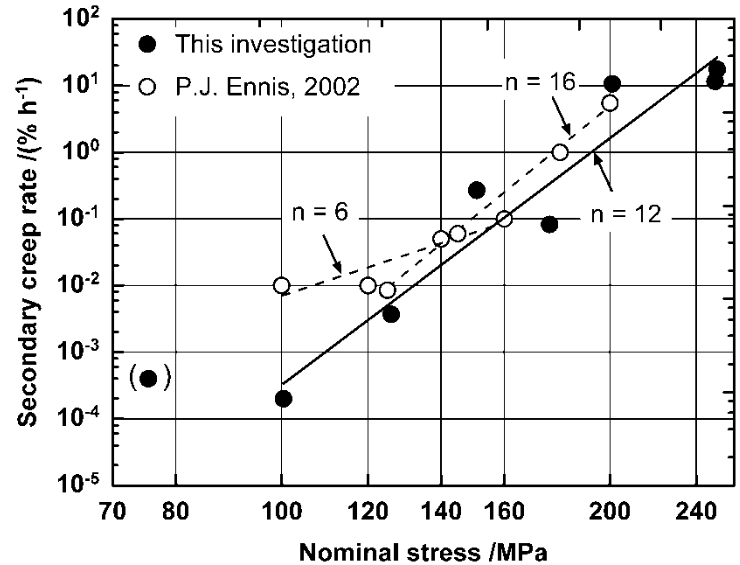




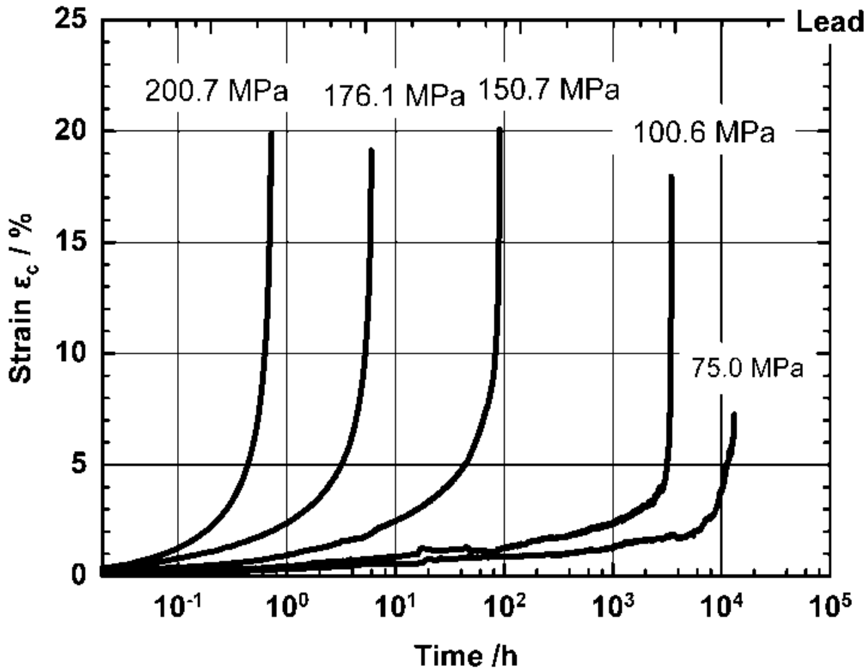
Norton equation:

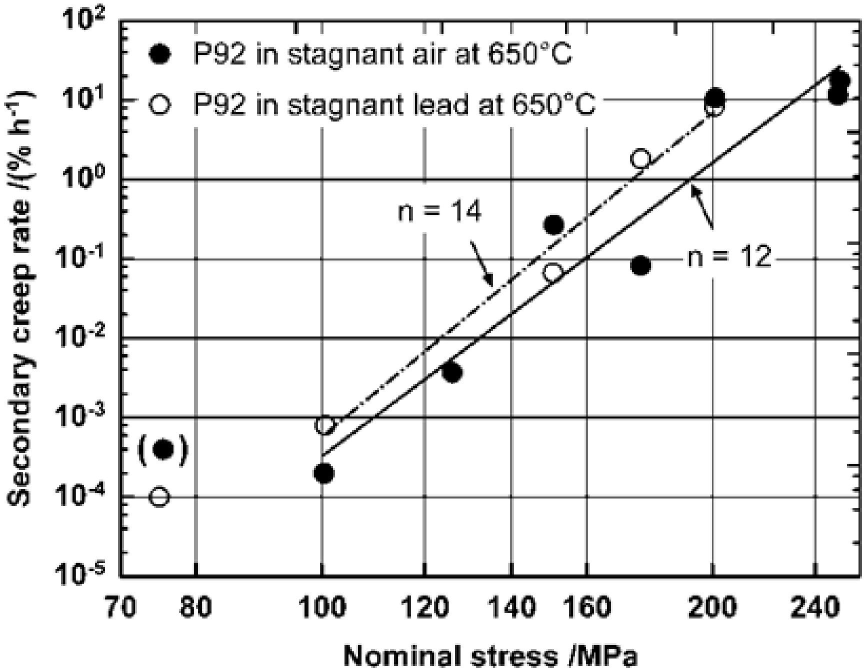
$$\dot{\varepsilon} = k\,\sigma^{n}$$



- ✓ Stress exponent n measured in air (=12) is close to literature data (n=16) at σ>125 MPa

Creep-to-rupture tests in Pb at 650°C

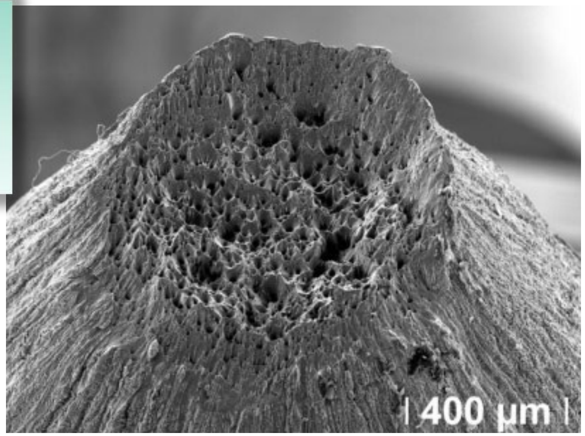


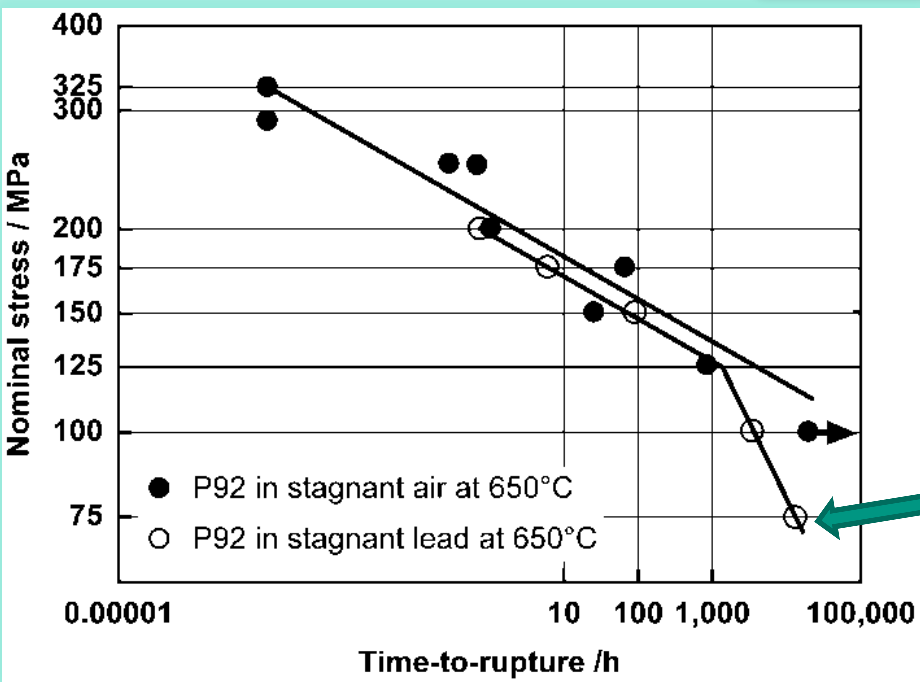


- ✓ Well-developed tertiary domain at >100 MPa and less pronounced at 75 MPa.
- ✓ Stress exponents n for P92 in air and in Pb are 12 and 14, respectively, at σ>100 MPa

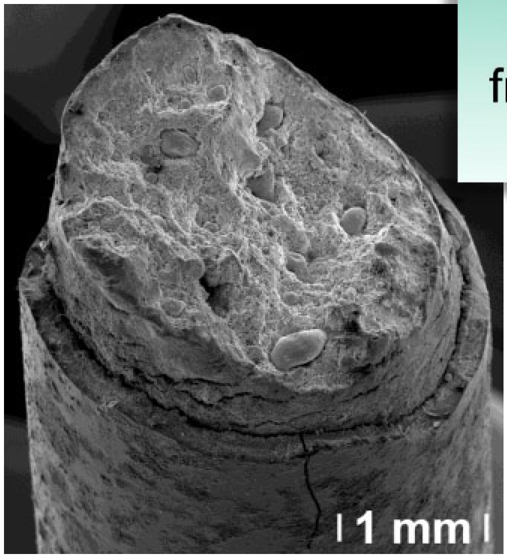
Creep-to-rupture tests in Pb and air at 650°C

✓ Ductile fracture in AIR and Pb at >100 MPa



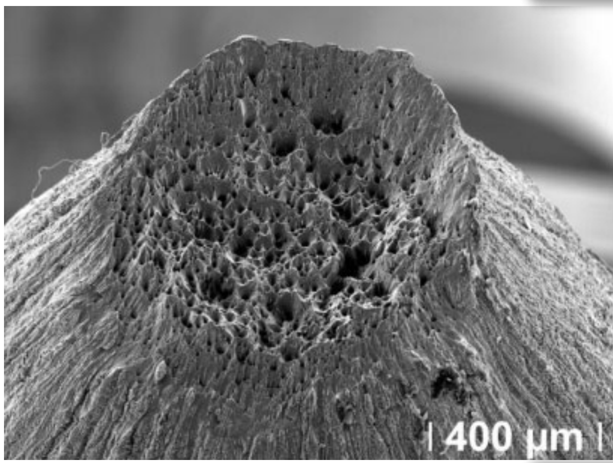


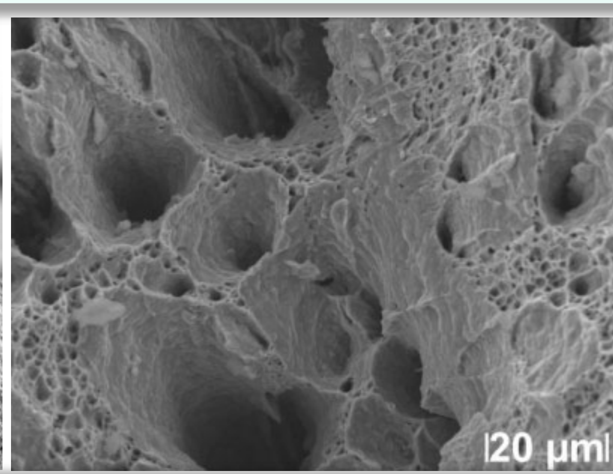
✓Brittle fracture in Pb at 75 MPa

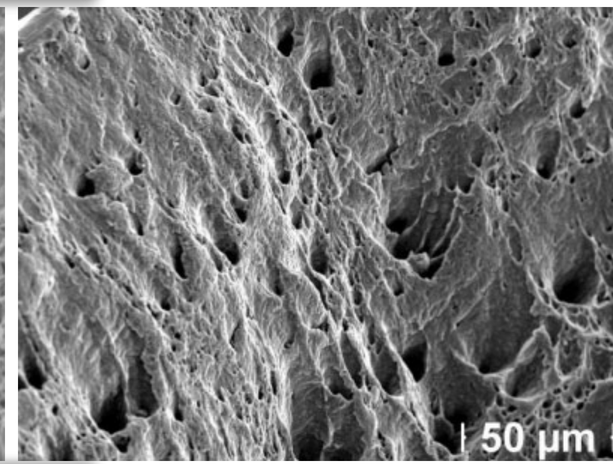


Post-exposure study of P92 tested in air

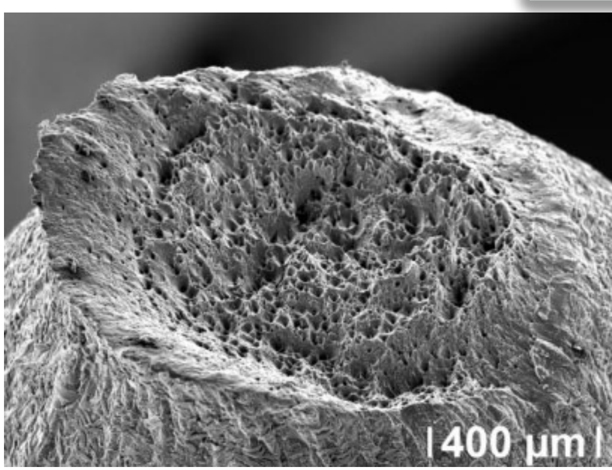
✓ P92 in air at 125 MPa

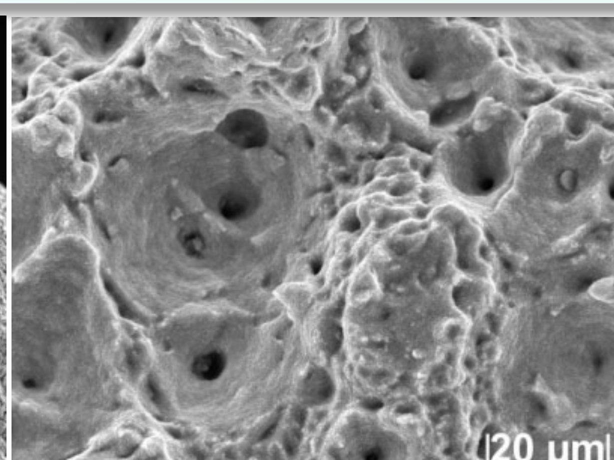


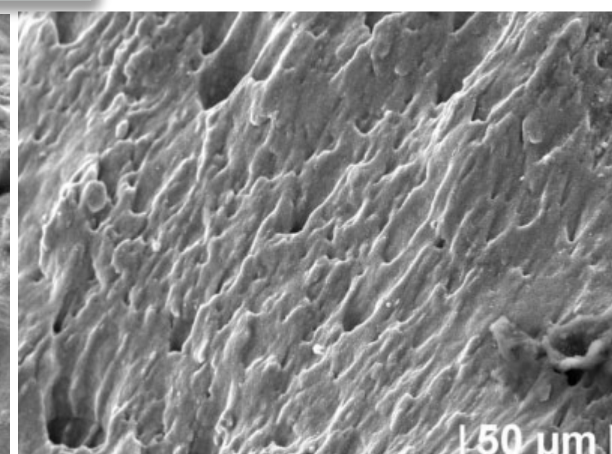




✓ P92 in air at 325 MPa

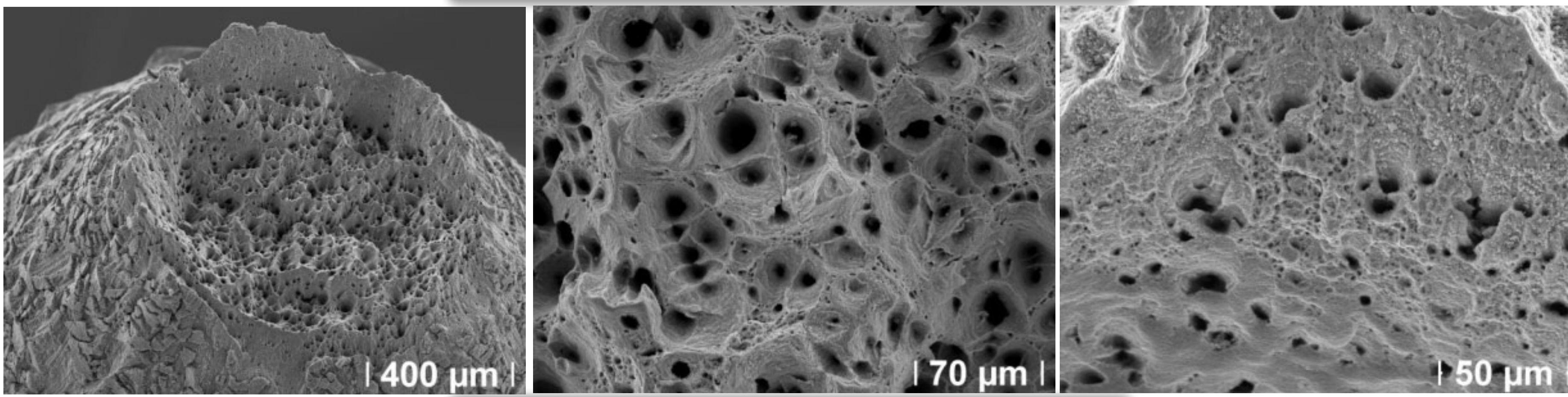




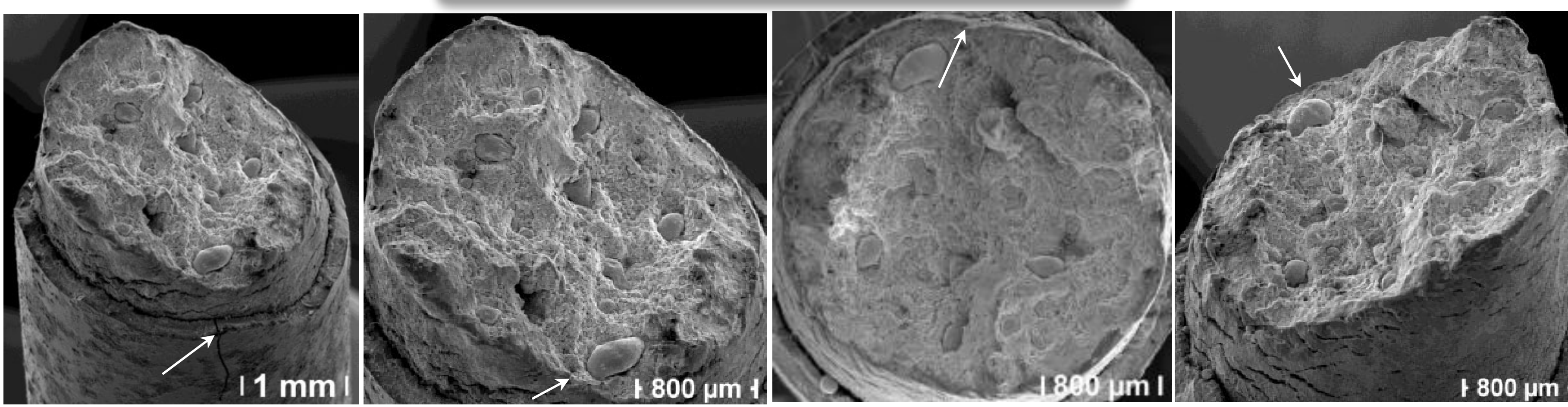


Post-exposure study of P92 tested in Pb and air

✓ P92 in Pb at 150 MPa



✓ P92 in Pb at 75 MPa (LME)



Post-exposure study of P92 tested in Pb and air

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✓ Creep-to-rupture characteristics of P92 at 650°C

✓ in stagnant air

σ MPa	t_R h	$\varepsilon_{c;R}$ %	Z %	$\dot{\varepsilon}_{c,s}$ %/h	$t_{1,2}$ h	$t_{2,3}$ h
325.5	0	20	83	-	-	-
290.3	0.017	31	89	-	-	-
250.7	0.3	20	90	17.68	0.083	0.12
249.7	0.68	21	86	11.63	0.217	0.33
201.0	1.0	31	90	10.68	0.317	0.65
176.0	65.5	28	89	0.083	5.133	37.4
150.9	25.1	31	91	0.270	1.933	12.4
126.0	839.1	23	83	0.004	147.2	610
100.4*	>12,150	-	-	0.0002	337.8	-
75.5*	>1,104	-	-	0.0004	81.5	-

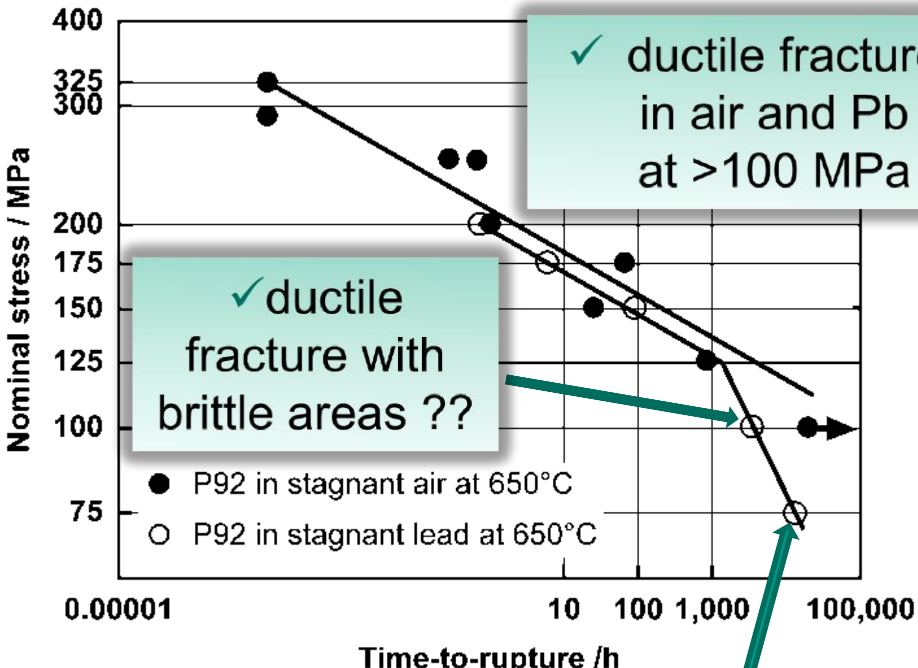
* Test was stopped before rupture

✓ in stagnant Pb

σ MPa	t_R h	$\varepsilon_{c;R}$ %	Z %	$\dot{\varepsilon}_{c,s}$ %/h	$t_{1,2}$ h	$t_{2,3}$ h
200.7	0.73	23	92	8.4034	0.183	0.23
176.1	5.97	16	89	1.8241	1.05	2.73
150.7	90.0	18	90	0.0670	18.67	46.78
100.6	3,442	27	94	0.0008	597.6	2477
75.0	13,090	13	23	0.0001	1276	6363

- ✓ *In stagnant air*: $\varepsilon_{c;R}$ and *Z* are in ranges of 20-31% and 83-91%, respectively.
- ✓ *In stagnant Pb*: at >100MPa $\varepsilon_{c;R}$ and *Z* are similar to that in air. At 75MPa they are much smaller.

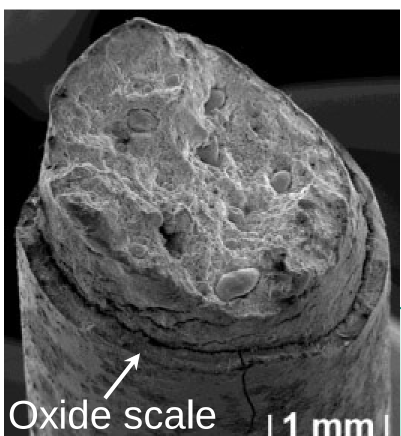
Post-exposure study of P92 tested in Pb and air



✓ ductile fracture in air and Pb at >100 MPa

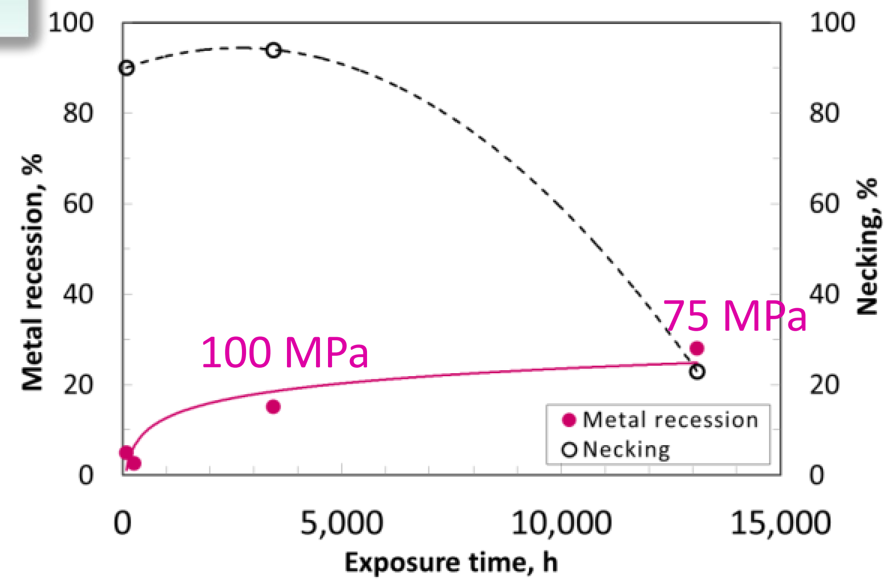
✓ductile fracture with brittle areas ??

✓brittle fracture with small $\varepsilon_{c;R}$ and Z



✓P92 in Pb at 75 MPa (t_R=13,090h)

Metall recession and necking of P92 in Pb at 650°C



Except Pb effect (change in failure mechanism), a reduce of the load-bearing cross-section is the next factor of steel degradation.

Post-exposure study of P92 tested in Pb and air

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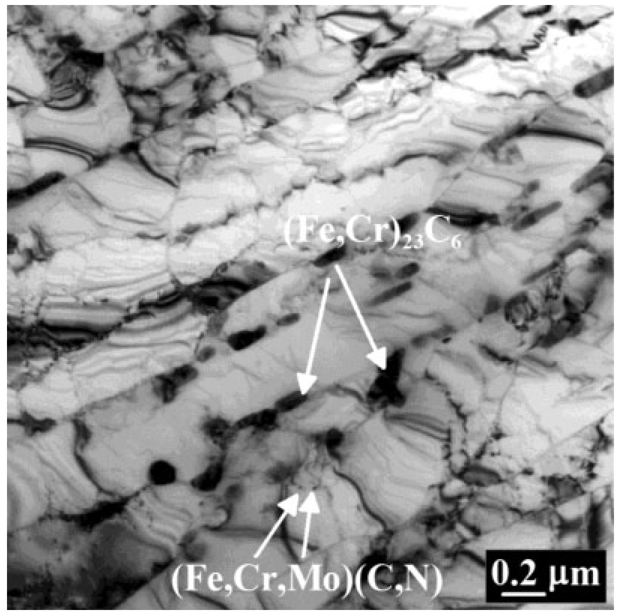
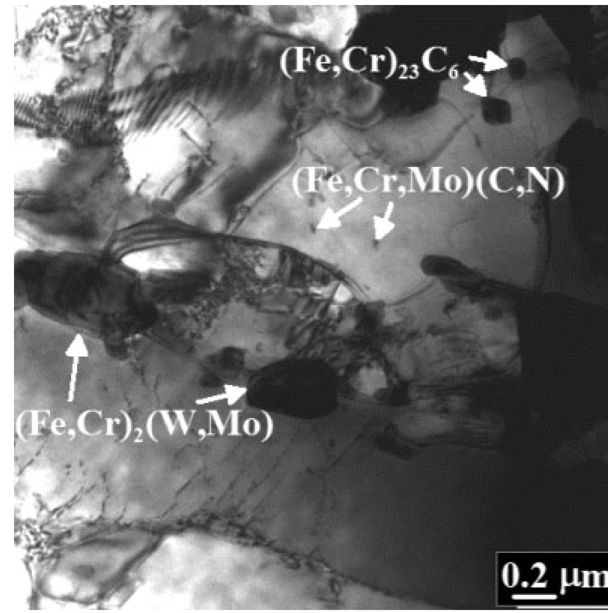
✓ as-received
(normalsing @1060°C/1h & tempering @ 770°C/2h)



✓ after rupture in Pb
@75MPa and t_R=13,090h



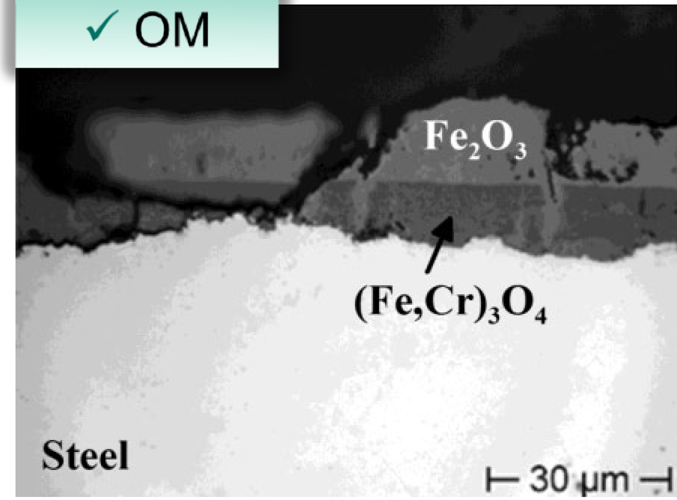
Independent of the medium:

- ✓ martensitic laths increased in size.
- ✓ $M_{23}C_6$ - carbides and MX - carbo-nitrides coarsen with aging time;
- ✓ the Laves phase precipitates at grain boundaries during exposure and grows with time.

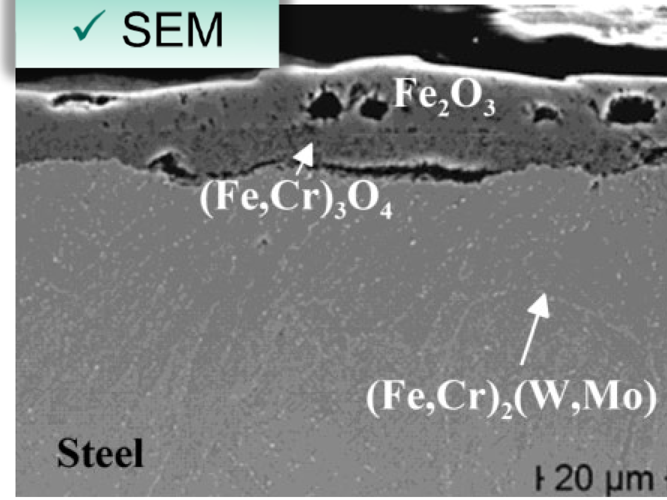
Post-exposure study of P92 tested in air

✓ OM

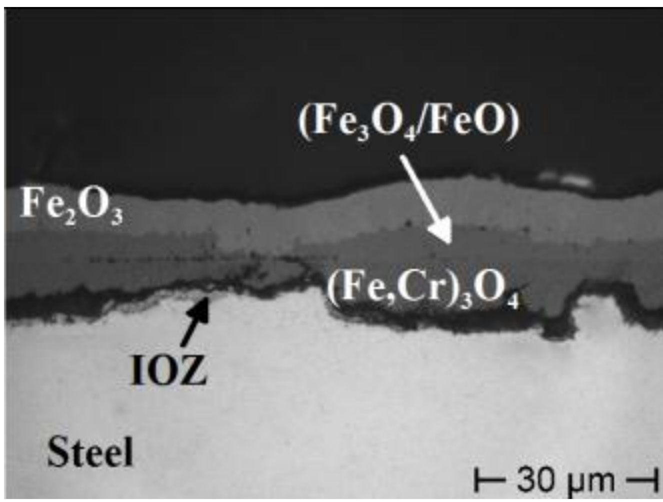
✓ SEM



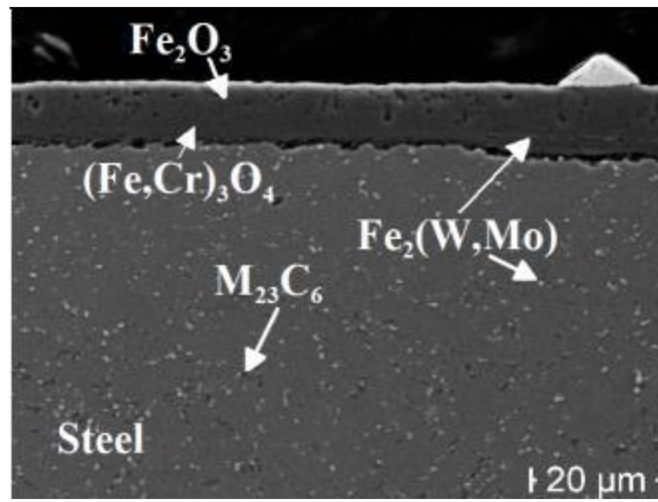
necking area



126MPa 839h



away from failure

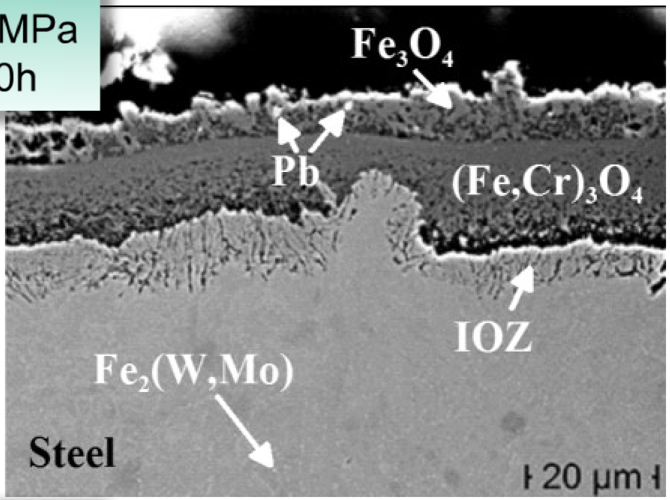


100MPa 12,121h

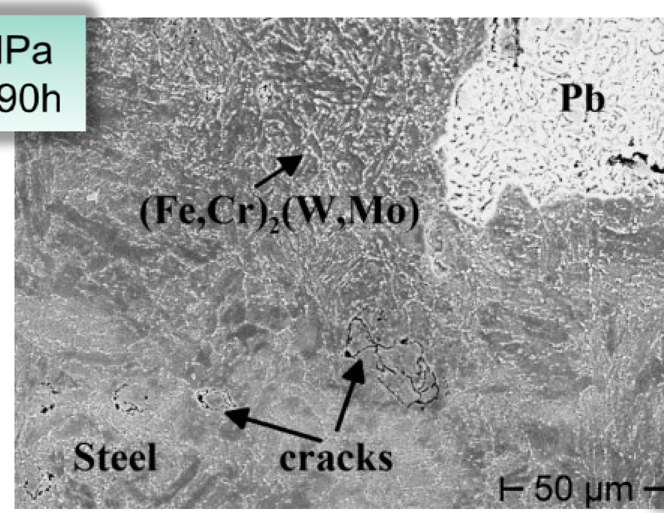
- ✓ Coarsening of Laves phase due to Ostwald ripening.
- ✓ Formation of Fe_2O_3 in $(Fe,Cr)_3O_4$ in the necking area. Formation of an oxide layer with a higher Fe-content on top of $(Fe,Cr)_3O_4$ away from the failure.

Post-exposure study of P92 tested in Pb

150MPa
90h

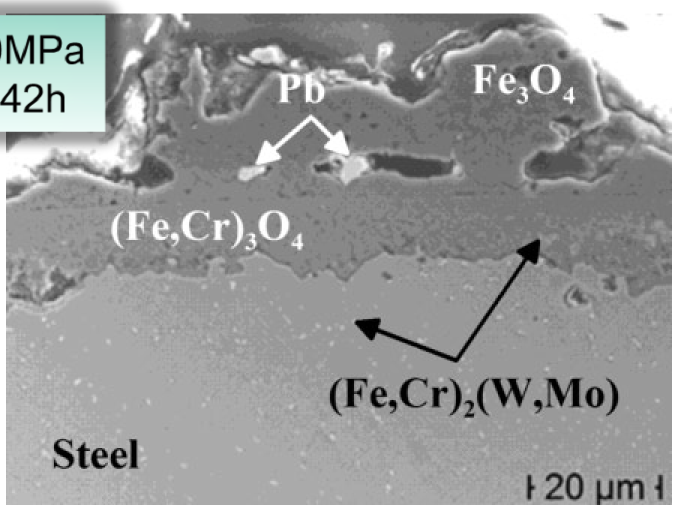


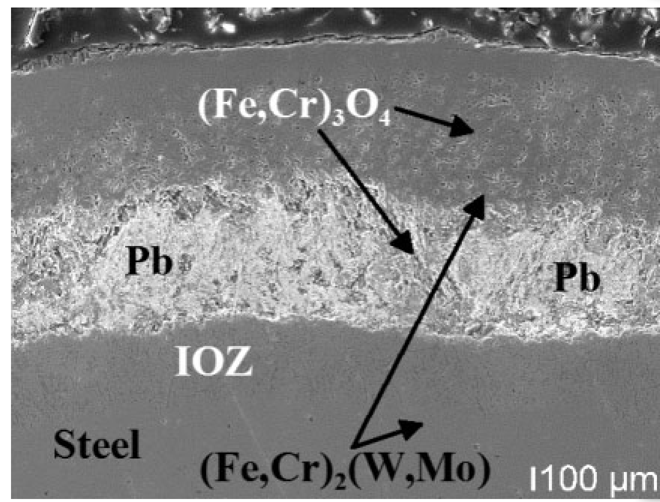
75MPa
13,090h



longitud.

100MPa
3,442h





perpendic.

- ✓ Infiltration of Pb in the oxide scale along cracks in short-term tests.
- ✓ Pb-Penetration in the inward growing oxide layer and steel in long-term tests.

Conclusion

- ✓ Negligible effect of liquid Pb (in comparison to oxidation in air) on creep strength at >125 MPa and 650°C.
- ✓ Long exposure time (slow secondary creep at low stresses) favors LME in steel exposed to Pb.
- ✓ The next decisive factor (resulted in ductile fracture): Loss of load-bearing cross-section due to oxidation.
- ✓ Coarsening of Laves phase in long-term tests introduces the 3rd degradation process in long-term experiments.

Outlook

- ✓ Additional tests – to separate clearly the effects. The focus on long-term tests or low sresses.

Acknowledgment

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