Swelling

- First discovered in 1986-UK

- Occurs when vacancies collect into clusters which grow and cause the material to expand

- Has been observed in many pure metals and alloys (Mg, Al, V, Fe, Co, Ni, Cu, Nb, Mo, Ta, W, Re, and Pt) and dozens of alloys.

- Generally occurs between 30 and 50% of the absolute melting point.

(Figures)

- Usually try to keep swelling <<10% (i.e., 1-2%)

- Limits the operating life to 2-3 FPY's in austenitic steels and 5-7 FPY's in ferritic steels.

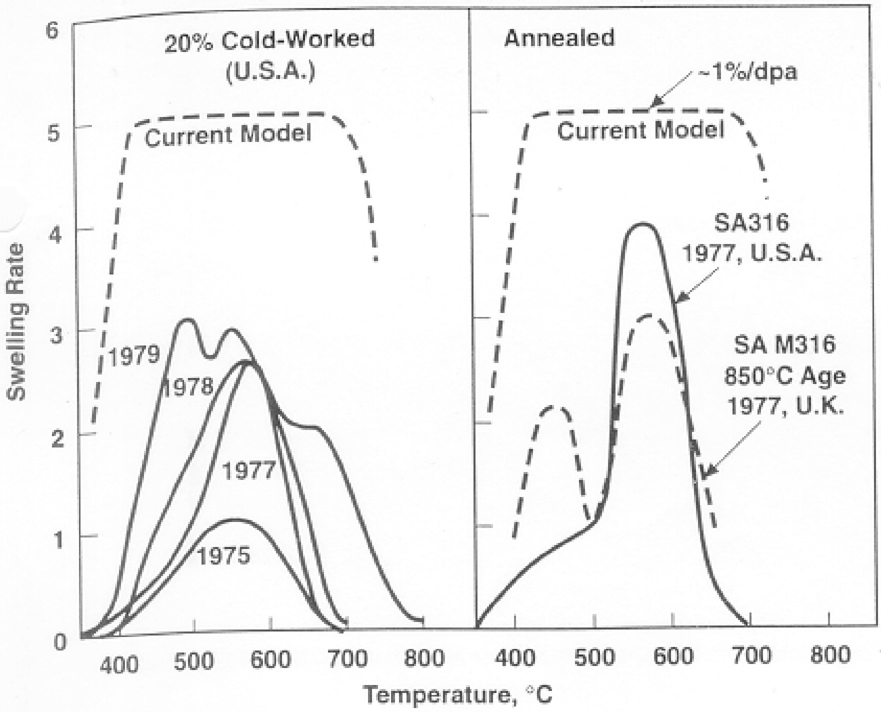


Figure 6-22. Chronological evolution of swelling predictions for AISI 316 in the U.S. LMR materials program, reflecting the tendency of predictions to increase as data became available at progressively higher swelling levels (Garner, previously unpublished). The swelling rate is in units of $\%/10^{22}\ \mathrm{n\ cm^{-2}}$ ($E > 0.1$ MeV).

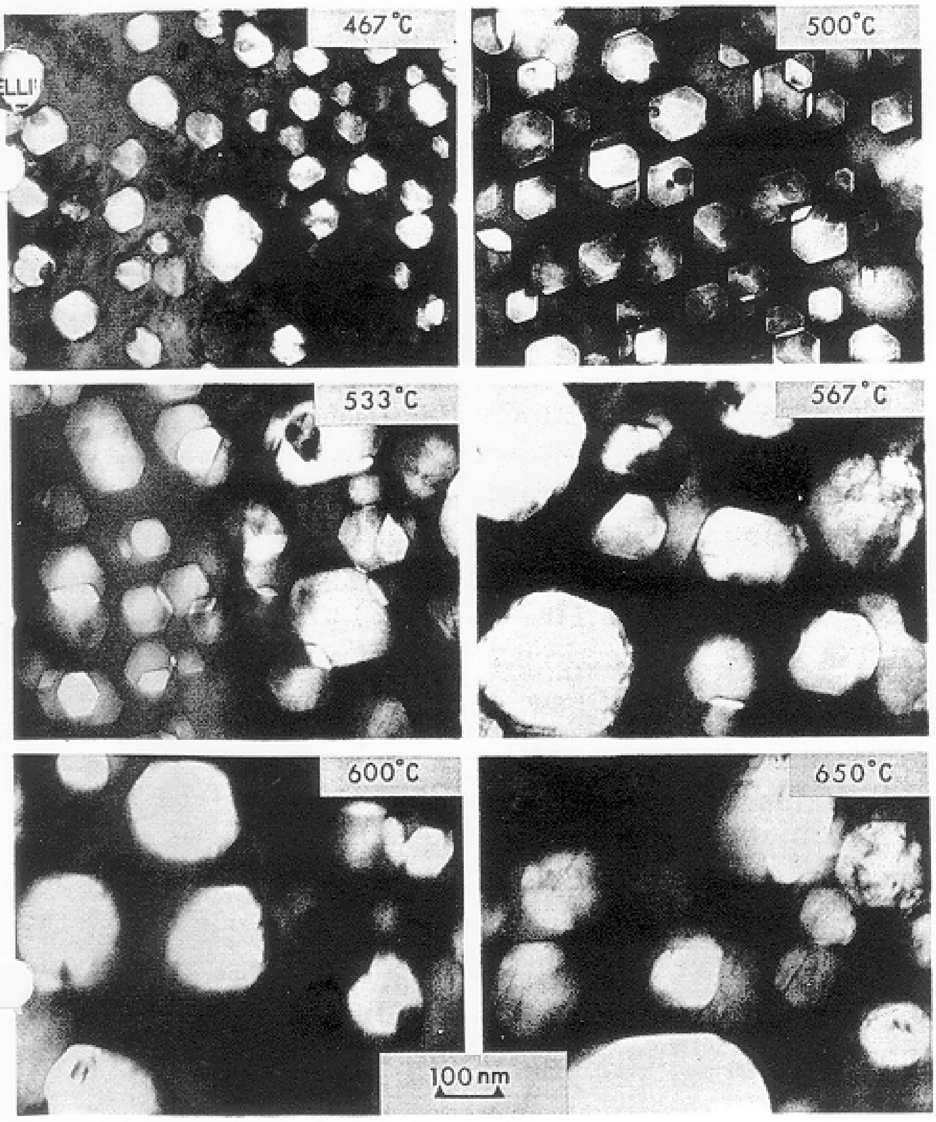


Figure 6-23. Temperature dependence of void swelling observed in FFTF first core heat CN-13 of 20% cold worked AISI 316 at $\approx 1.4 \times 10^{23}\ \mathrm{n\ cm^{-2}}$ ($E > 0.1$ MeV) or ≈ 70 dpa (courtesy of W. J. S. Yang of Westinghouse Hanford Company).

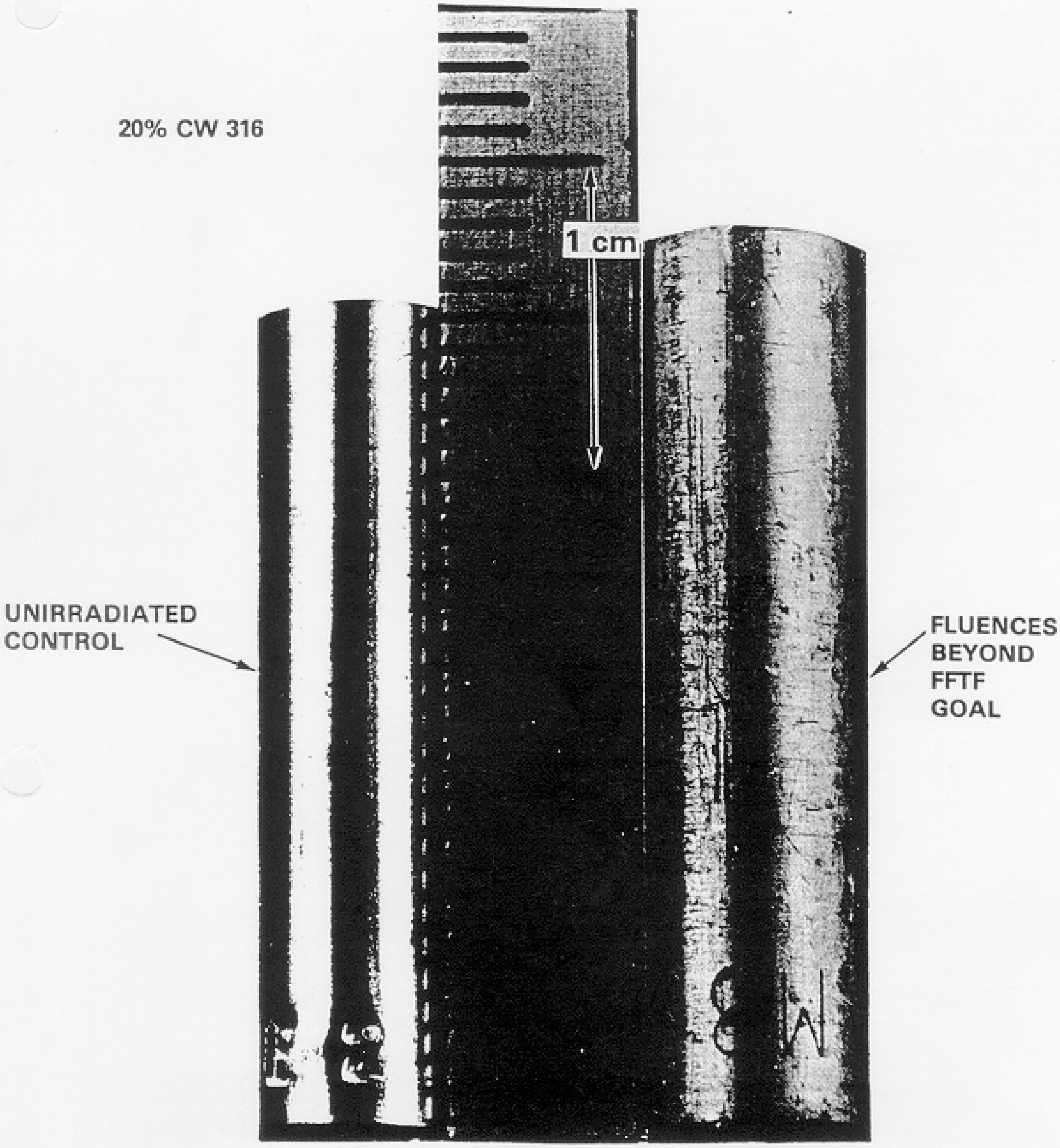


Figure 6-24. Easily observed swelling ($\approx$10% linear, $\approx$33% volumetric) in unfueled 20% cold worked AISI 316 cladding tube at 1.5×10^{23} n cm^{-2} ($E > 0.1$ MeV) or $\approx$75 dpa at 510 °C in EBR-II (after Straalsund et al., 1982). Note that, in the absence of physical restraints, all relative proportions are preserved during swelling.

SWELLING ESTIMATES OF TYPE 316
STAINLESS STEEL 20% COLD WORKED
(AUG. 1969)

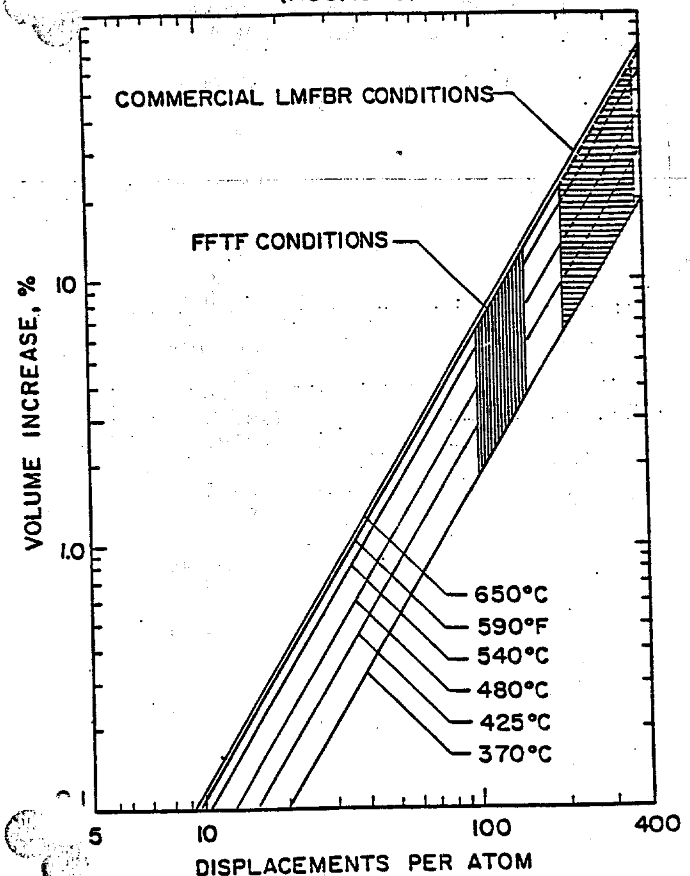
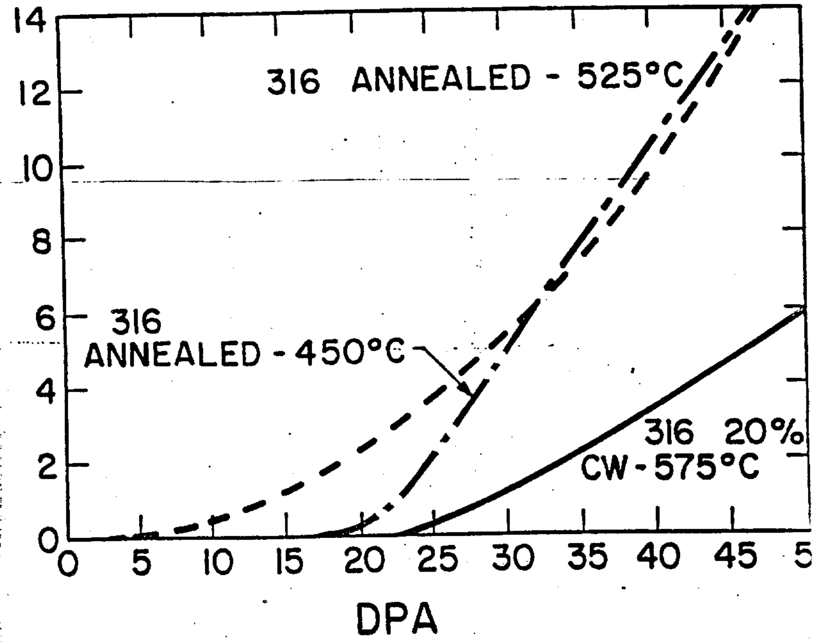


FIGURE 5



TYPICAL SWELLING IN AUSTENITIC STEELS

PREDICTED SWELLING FOR
SOLUTION TREATED 316 STAINLESS STEEL
AT 2.5×10^{23} n/cm^2 (E>0.1 MeV)

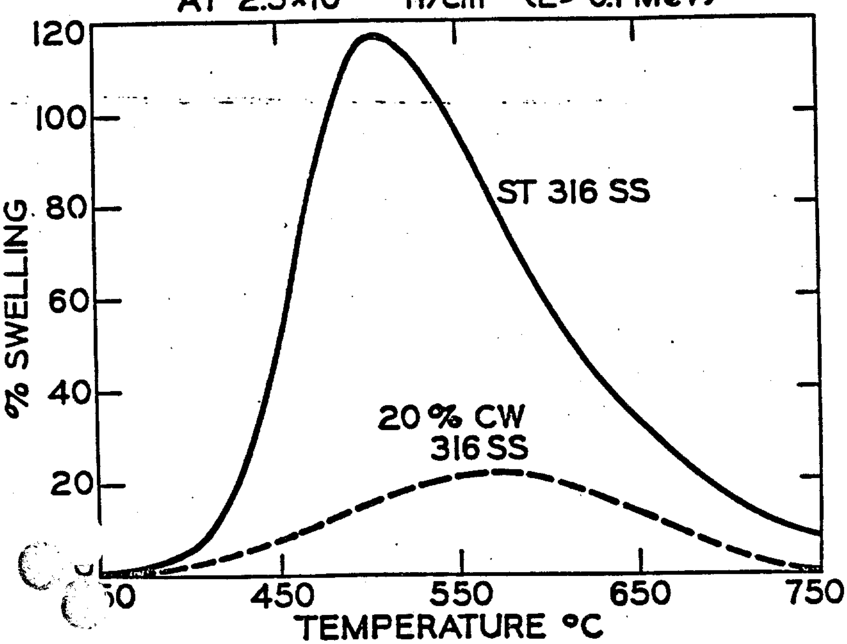
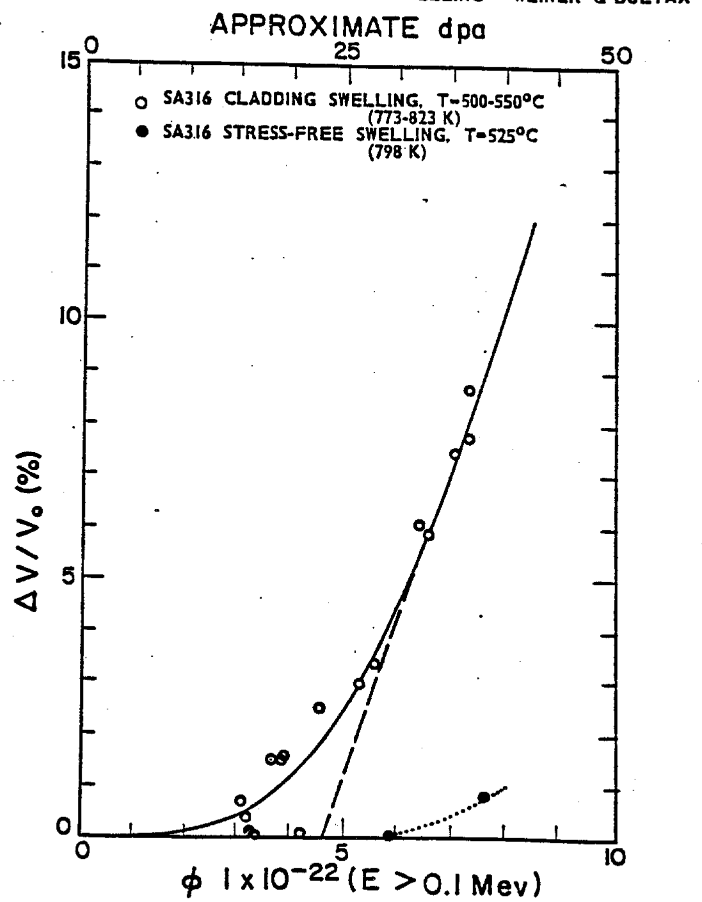


FIGURE 21 STRESS EFFECT ON SWELLING - WEINER & BOLTAX



Embrittlement

- Loss of ductility due to helium collecting at grain boundaries.

- Try to keep the uniform elongation > 1%

- In ferritic steels, the shift in the ductile to brittle transition temperature is the important thing.

(Figures)

Overall Conclusions

- In DT devices , displacement and transmutation effects will limit useful lifetimes to a few full power years. Hence replacement of the FW, blanket, components will have to be done on a regularly scheduled basis.

- Use of advanced fuels will drop the neutron wall loading by a factor of ≈ 30 which means that the structural materials can last for the life of the reactor.

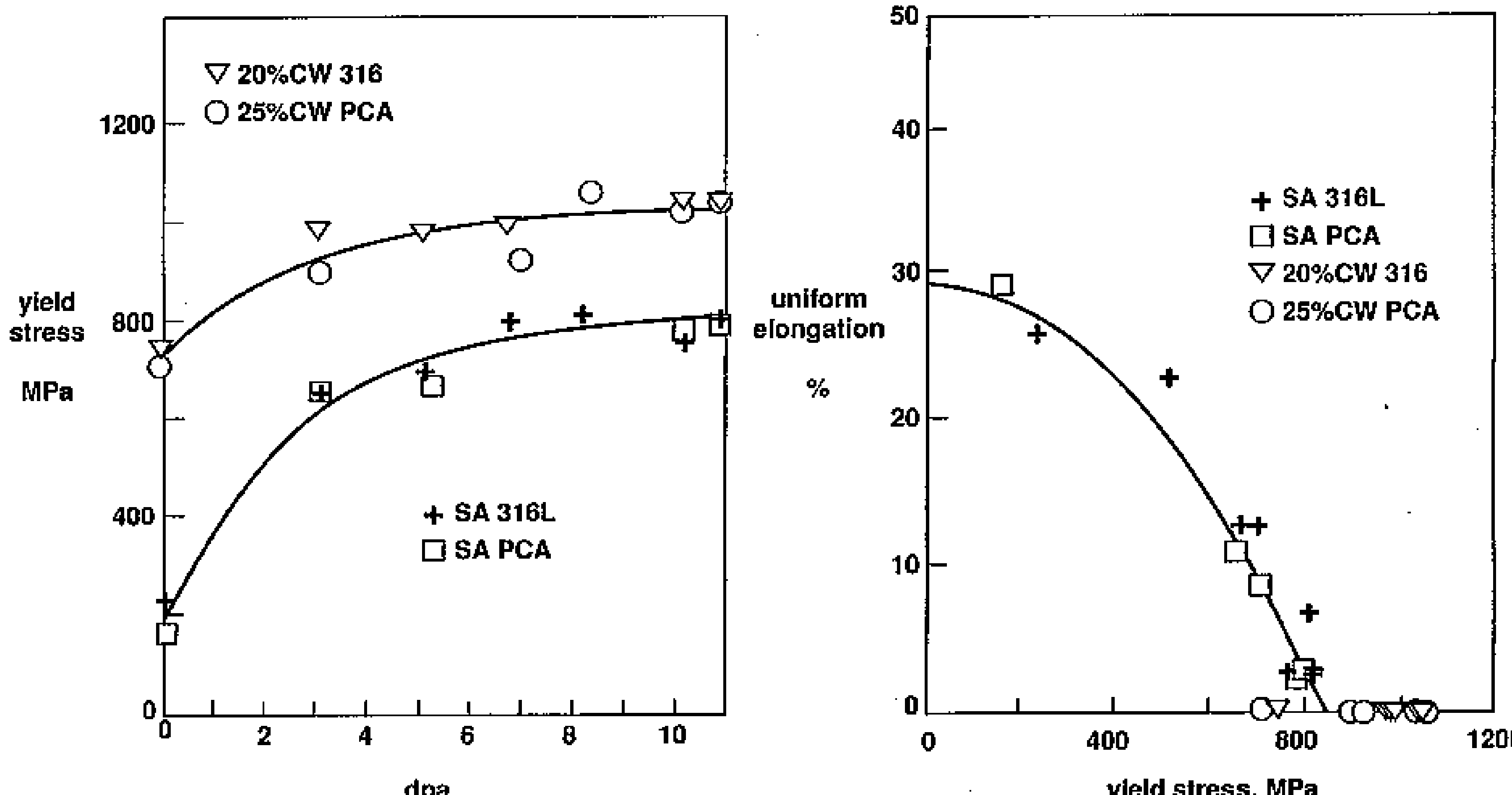


Figure 6-146. Hardening and ductility loss observed in two stainless steels irradiated in the HFIR, HFR, and R2 mixed spectrum reactors at 250°C at helium/dpa ratios ranging from 10 to 35 appm/dpa (after Elen and Fenici, 1992).

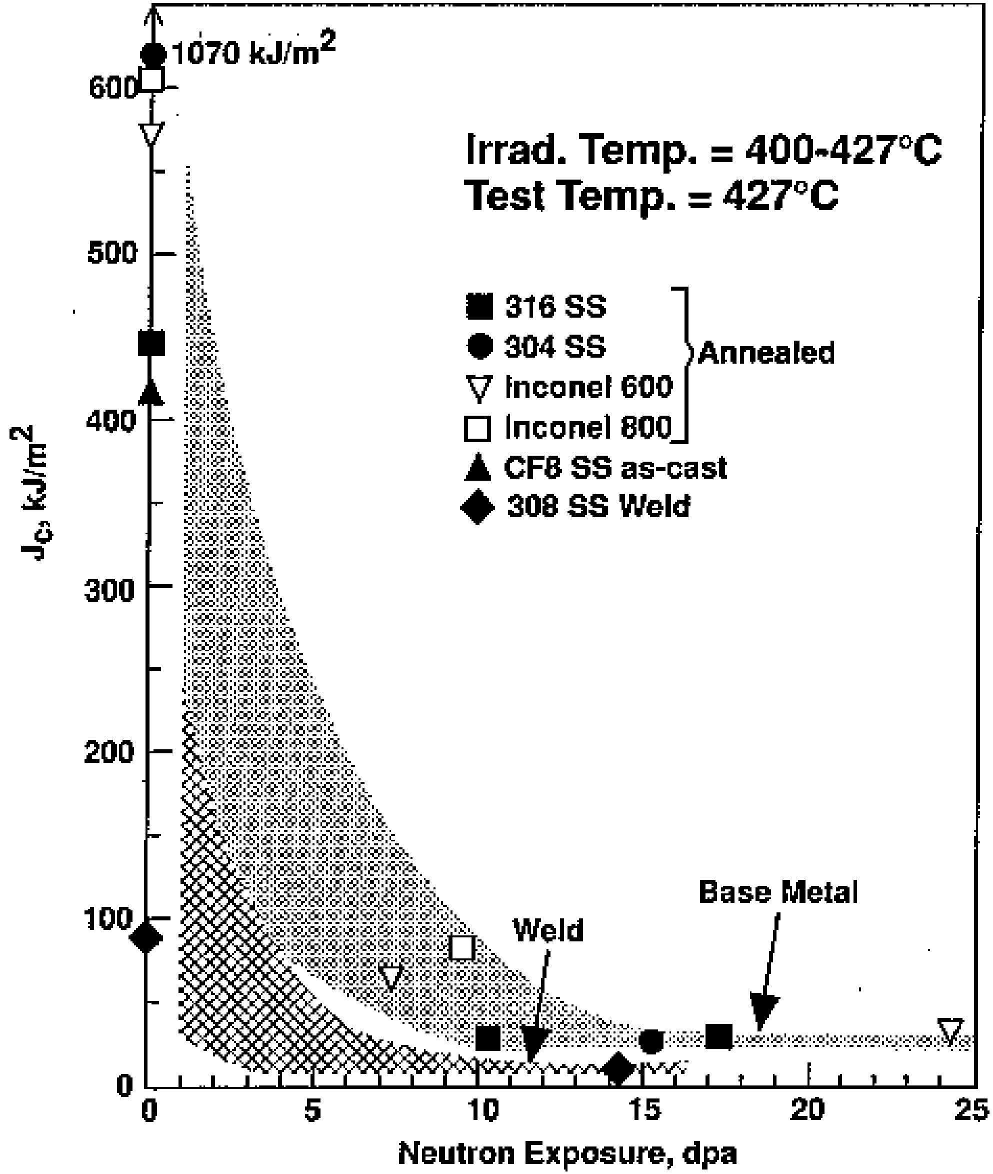


Figure 6-163. Irradiation-induced evolution of J_c fracture toughness in various austenitic steels and welds (after Mills, 1982).

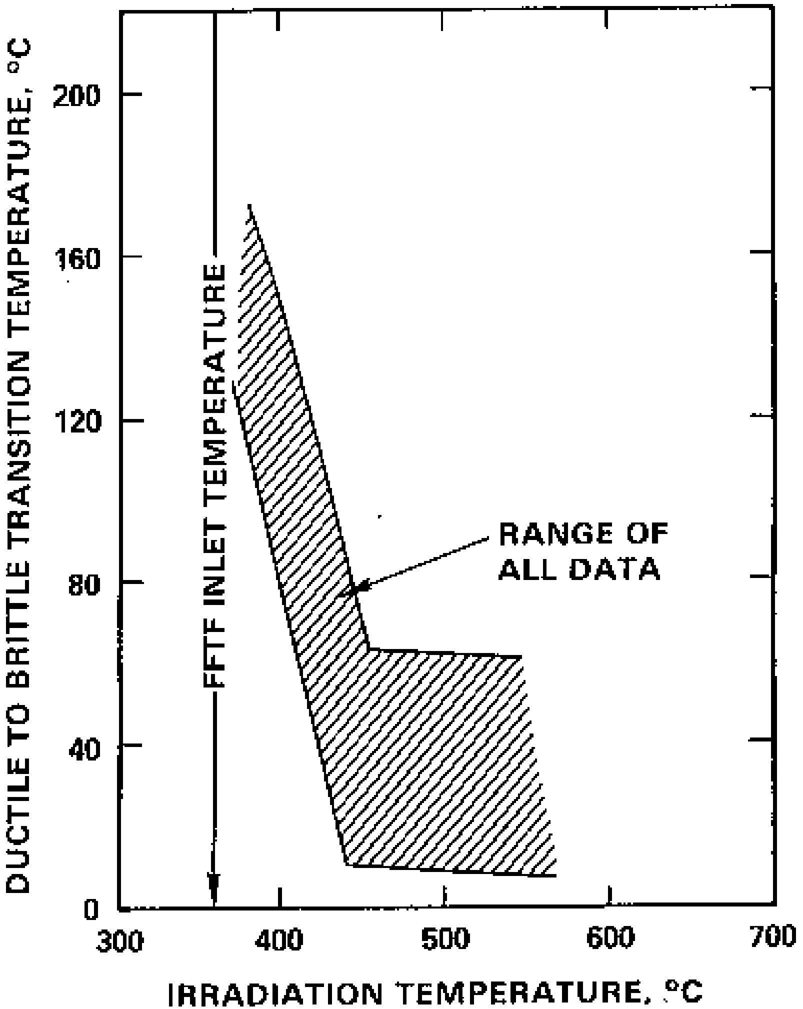


Figure 6-168. Dependence of DBTT on irradiation temperature for HT9 irradiated in FFTF (unpublished data courtesy of W. L. Hu, Westinghouse Hanford Company).

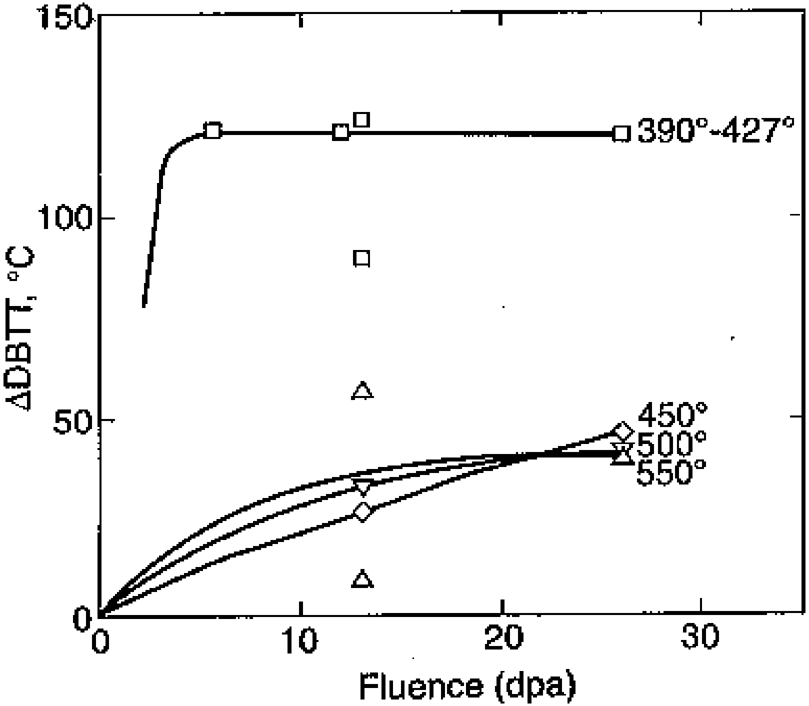


Figure 6-170. Shift in ductile to brittle transition temperature in HT9 as a function of neutron fluence and irradiation temperature (after Powell et al., 1986).

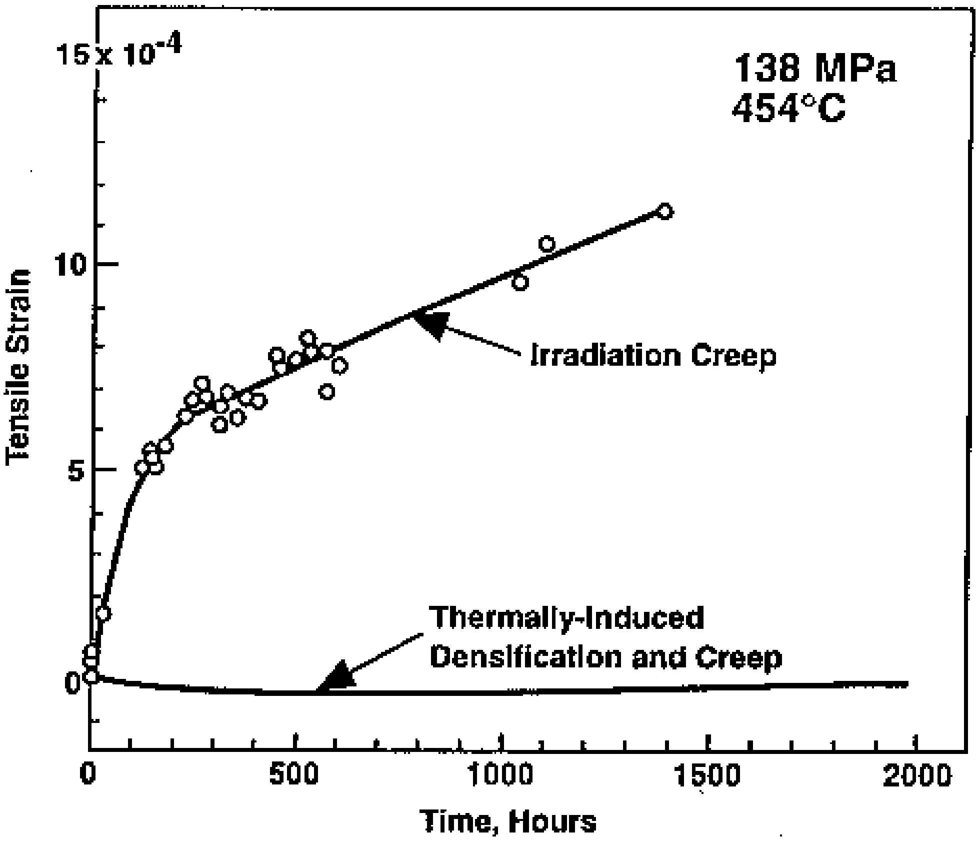


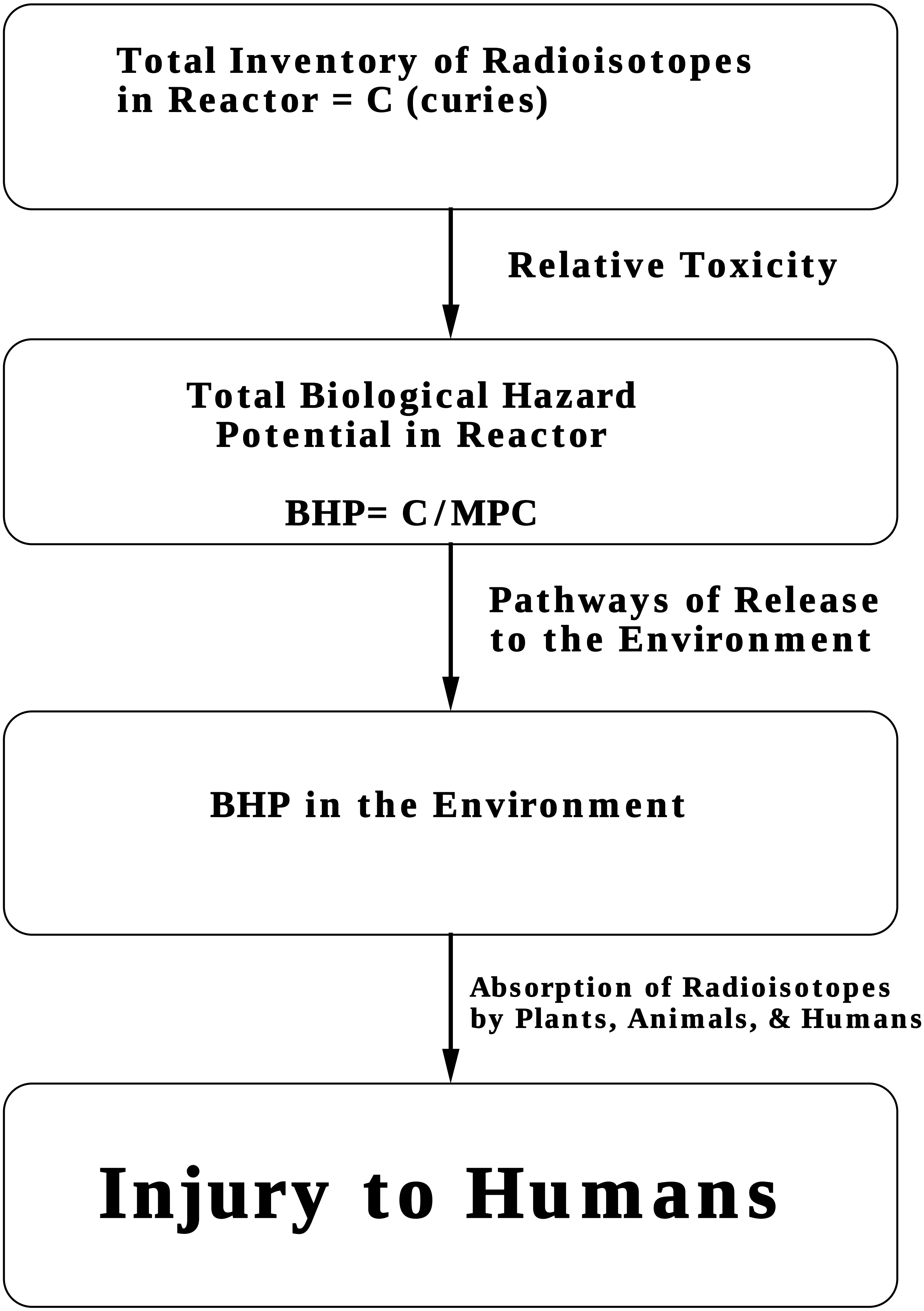
Figure 6-92. Comparison of creep rates observed in 20% cold worked 316 stainless steel in uniaxial tests during thermal aging or neutron irradiation in EBR-II (after Gilbert et al., 1972).

Criteria for Selecting First Wall Materials in Fusion Reactors*

Criteria	Favored Materials	Less Favored
Radiation Damage and Lifetime		
1) Swelling	Ti, FS**, V, Mo, AS**	Al, C, SiC
2) Embrittlement	AS, Ti	FS, V, Mo, C, SiC
Chemical Compatibility		
1) Lithium	Mo, V, FS, AS, Ti	(SiC, Al, C)
2) Helium (impurities)	Mo, FS, AS, C, SiC	Ti, Al, (V)
3) Pb-Li Alloys	Mo, V, FS, AS, Ti, SiC, C	Al
4) Water	AS, FS, Mo, Ti, Al	V, (SiC, C)
Mechanical and Thermal		
1) Yield Strength	Mo, Ti, V, FS, AS	SiC, C, Al
2) Embrittlement	AS, Ti, Al, Mo, FS	V, SiC, C
3) Creep Strength	Mo, V, FS, AS, Ti	C, SiC, Al
4) Thermal Stress $\equiv \frac{2\sigma_y k(1-\upsilon)}{\alpha E}$	Mo, Al, V	Ti, FS, AS
Fabricability and Joining	AS, Al, FS, Ti	V, Mo, C, SiC
Database and Industrial Capability	AS, FS, Al, Ti, C	SiC, Mo, V
Long-lived Radioactivity	V, C, SiC, Ti, Al	FS, AS, Mo
Cost	Al, AS, FS, C	Ti, V, SiC, Mo
Resource Availability (USA)	C, SiC, Al, Ti, Mo, AS, FS	V

* Note: Only Base Metal Listed (i.e., Ti for Ti alloys, V for V alloys, etc.)
** AS for austenitic stainless steel, FS for ferritic steel
( ) Materials in parentheses are generally unacceptable with coolant.

Radioactivity Concerns From Fusion



Neutron Induced Activity in Fusion Structural Materials

- Associated with DT, DD, and even D^3He
- Very material dependent
- Design dependent (% structure, etc.)

Example

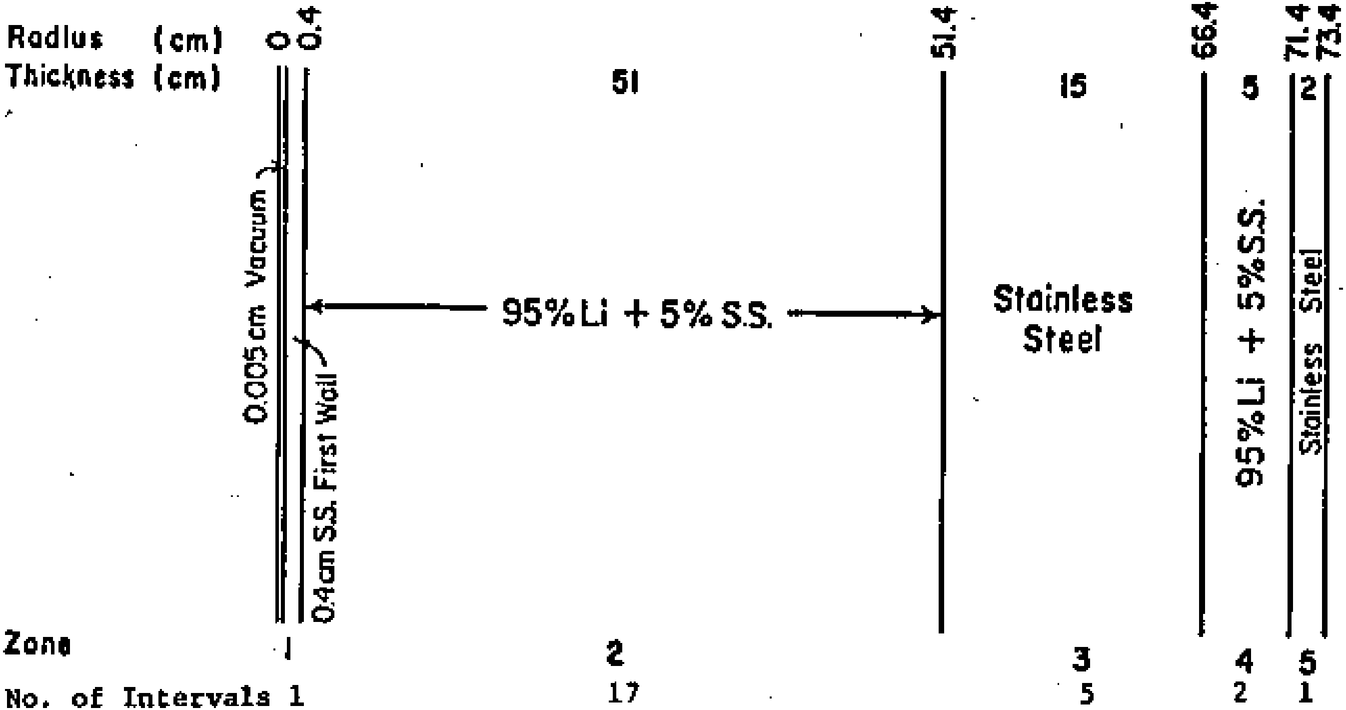
- DT
- 316 SS
- 2024 Al
- TZM
- V-20Ti
- Fixed Blanket Structure (see figure)

Use Calculational Procedure Developed by Sung-Vogelsang

"DKR-A Radioactivity Calculational Code for Fusion Reactors", UWFDM-170

"Decay Chain Data Library for Radioactivity Calculations", UWFDM-171

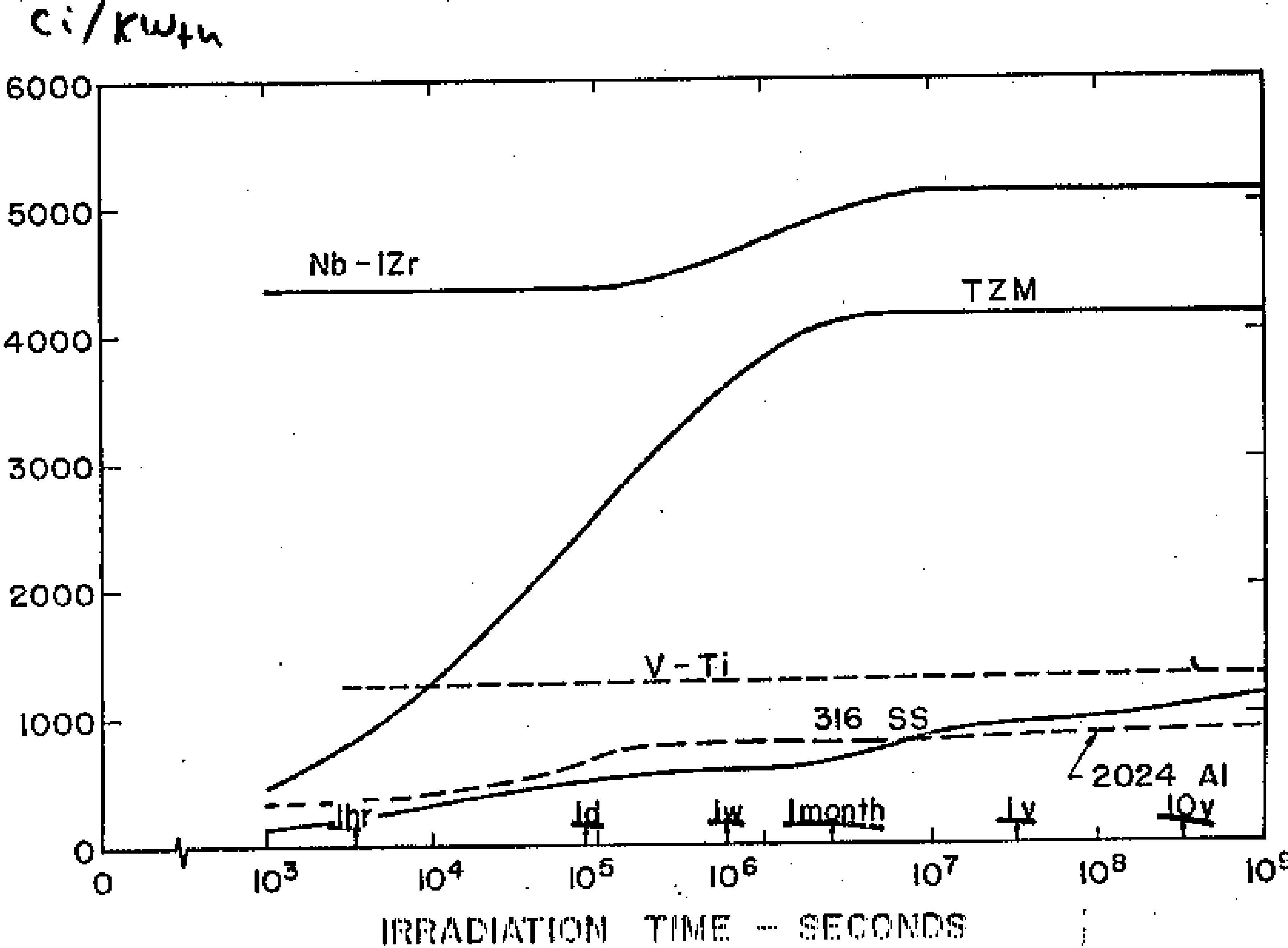
Tak Sung, PhD Thesis-Oct. 1976 "Radioactivity Calculations in Fusion Reactors"

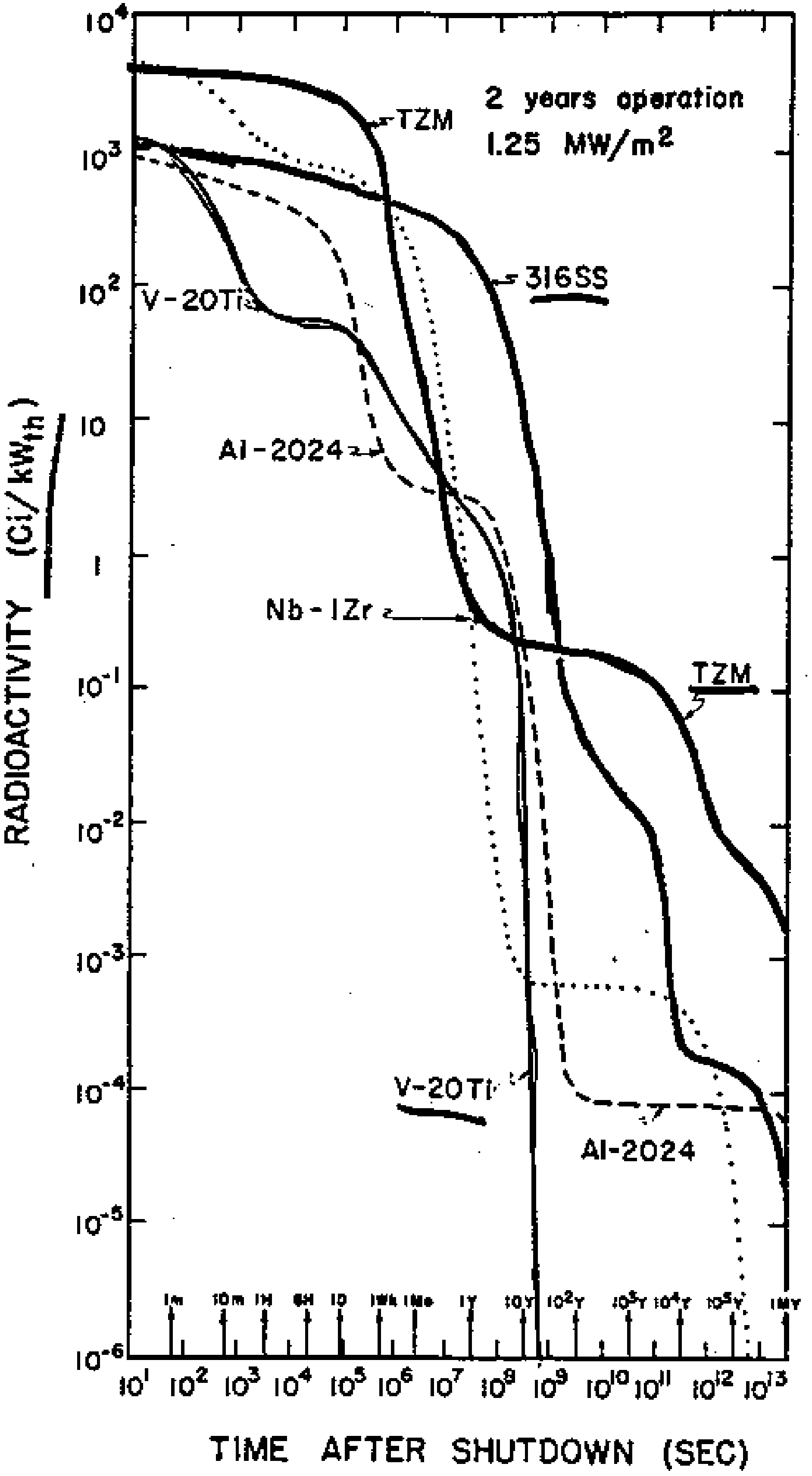


University of Wisconsin CTR Blanket Structure

UWMAK-I

Effect of Reactor Operation Time on Induced Activity in CTR Structural Materials





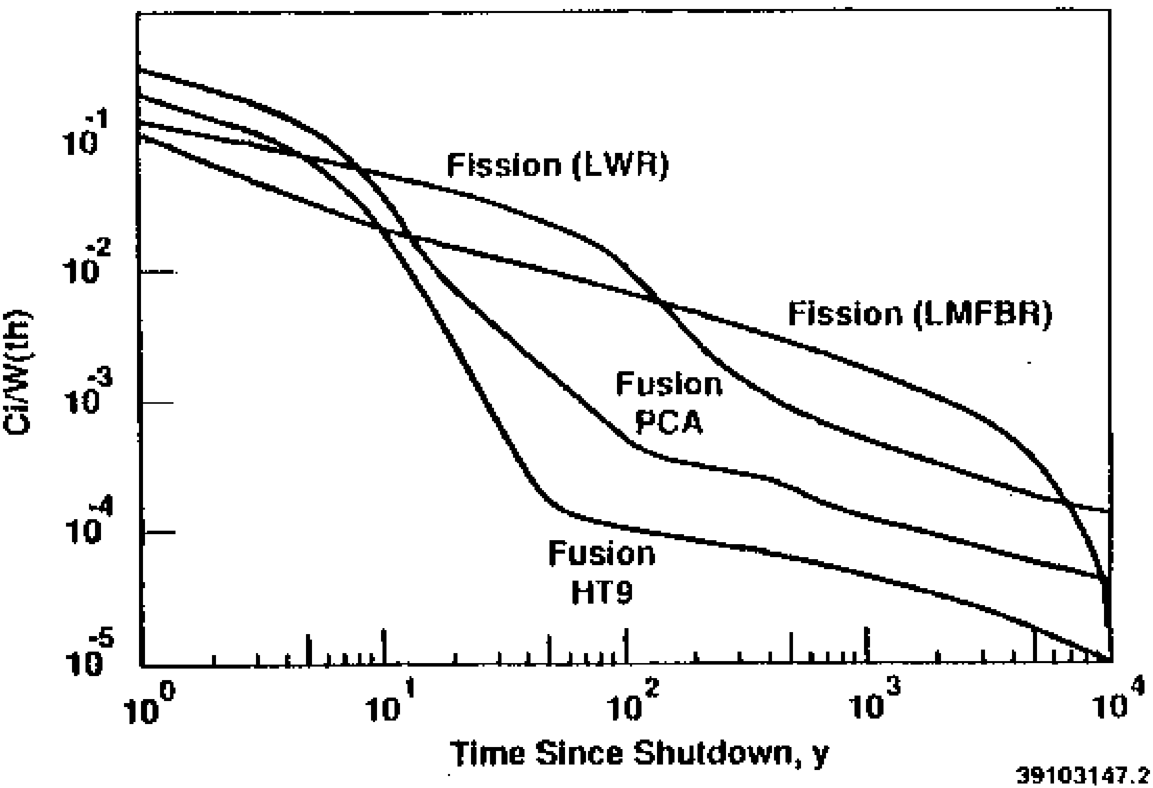
2 years operation
1.25 MW/m²
TZM
316SS
V-20Ti
Al-2024
Nb-1Zr
TZM
V-20Ti
Al-2024
RADIOACTIVITY (Ci/kWth)
TIME AFTER SHUTDOWN (SEC)
1m
10m
1H
6H
1D
1Wk
1Mo
1Y
10Y
10²Y
10³Y
10⁴Y
10⁵Y
1MY

Time to Decay to Specific Levels of Radioactivity in Various CTR Designs

Level-Ci/kW	316 SS	TZM	Nb-1Zr	V-20 Ti	2024 Al
Initial	*1,060*	*4,120*	*5,150*	*1,260*	*880*
1,000	**100 s**	**3 d**	**1 h**	**1 min**	**-**
100	**3 y**	**2 wks**	**1 mon**	**30 min**	**1 d**
10	**15 y**	**40 d**	**6 mon**	**2 wks**	**3 d**
1	**30 y**	**6 mon**	**1 y**	**3 y**	**4 y**
0.1	**60 y**	**3,000 y**	**1.5 y**	**10 y**	**20 y**
0.01	**2,000 y**	**40,000 y**	**2 y**	**15 y**	**30 y**
0.001	**5,000 y**	**1,000,000 y**	**5 y**	**20 y**	**40 y**

Radioactivity in Fission and Fusion Reactors

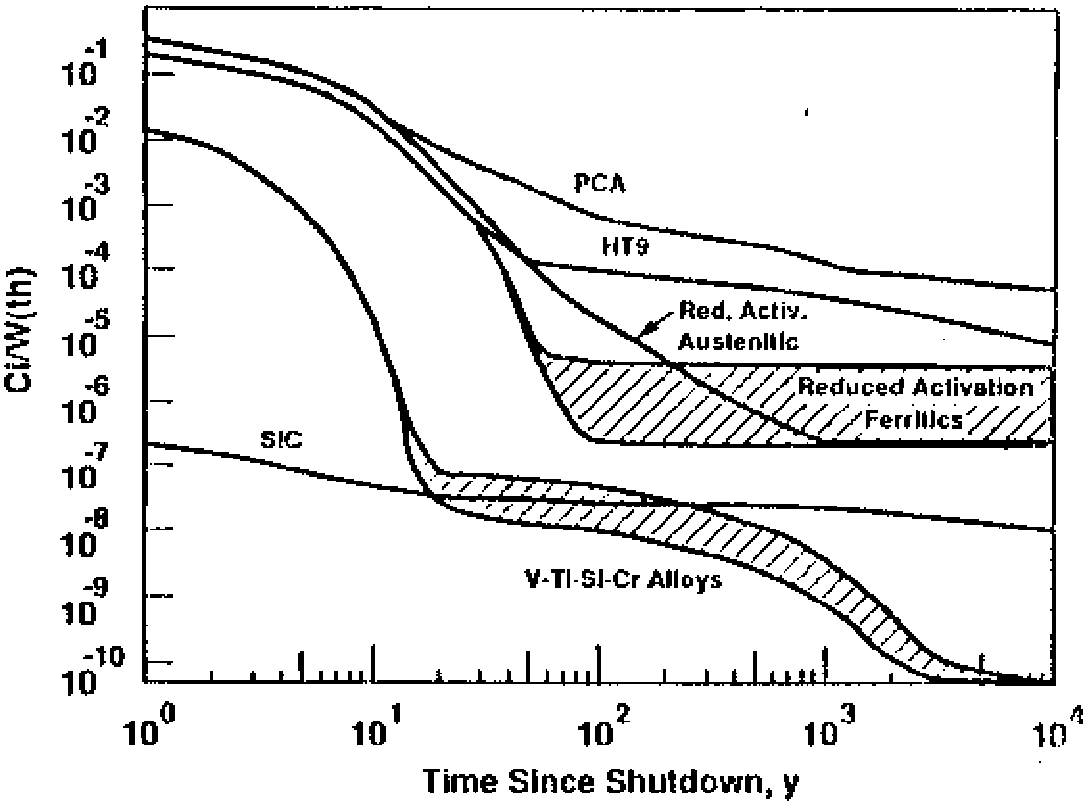
Total for 30 yr Reactor Lifetime



F. W. Wiffen

IEA Low Activation Materials Workshop
Culham, England April 8-12, 1991

Inventory of Radioactivity in a Fusion Reactor
STARFIRE, Total for 30 yr Reactor Lifetime



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IEA Low Activation Materials Workshop
Culham, England April 8-12, 1991

Elemental Composition of Normal and Reduced Activation Steels				
	Concentration in Wt. %			
Element	**PCA**	**Tenelon**	**HT-9**	**MHT-9**
B	0.005	0.001	0.01	0.001
C	0.005	0.15	0.2	0.15
N	0.01	0.005	0.05	0.001
O		0.007	0.01	0.007
Al	0.03	0.008	0.01	0.008
Si	0.5	0.2	0.35	0.2
P	0.01	0.13	0.02	0.013
S	0.005	0.004	0.02	0.004
Ti	0.3	0.003	0.09	0.1
V	0.1	0.002	0.3	0.3
Cr	14.0	15.0	12.0	11.0
Mn	2.0	15.0	0.55	0.53
Fe	64.88	69.4	85.0	85.2
Co	0.03	0.005	0.02	0.005
Ni	16.0	0.006	0.5	0.006
Cu	0.02	0.003	0.09	0.003
Zr	0.005	0.001	0.001	0.001
Nb	0.03	0.00011	0.0011	0.00011
Mo	2.0	0.00027	1.0	0.00027
Ag	0.0001	0.00009	0.0001	0.00009
Sn	0.005	0.003	0.003	0.003
Ta	0.01	0.0004	0.001	0.0004
W	0.05	0.01	0.5	2.50
Pb	0.001	0.0005	0.001	0.0005
Bi	0.001	0.0002	0.001	0.0002

The Reasons for Developing Low Activation Stainless Steels Have Not Always Been the Same

Waste Disposal	Near Surface Burial (Class C)
Safety	<10 Rem Maximum Early Dose
Maintenance	< 1 mrem/hr Contact Dose
Recycling	<u>Contact Dose</u> < 1 rem/hr , t<100 Y < 1 mrem/hr, t>100 Y

Why Develop Low Activation Stainless Steels?

For	Against
Reduce Long Term Radiation Level to Allow Near Surface Burial	Usually Aggrevates the Short Term Afterheat Problem
Reduce Long Term Waste Disposal Costs	Cost of Developing and Qualifying New Low Activation Alloy Can Be Substantual
Reduce Exposure to Workers if Alloy is Recycled	May Increase Short Term Radiation Levels and Increase Radiation Levels During Maintenance
Makes Fusion More Attractive to Environmentalists and Politicians	Time Involved in Developing and Qualifying Low Activation Materials May Delay the Implementation of Fusion

Radwaste Class	Period from Decay to Acceptable Level	Meets Minimum Waste Form Requirements	Meets Stability Requirements	Provide an Intruder Barrier	Depth of Burial
A	**<<100 years**	**Yes**	**No**	**No**	**<<5 m**
B	**< 100 years**	**Yes**	**Yes**	**No**	**< 5 m**
C	**< 500 years**	**Yes**	**Yes**	**Yes**	**> 5 m**
Deep Burial	**> 500 years**	**Yes**	**Yes**	**Yes**	**Deep Geological Burial**

The "Everything Goes Deep" Philosophy

One School of Thought at the IEA Workshop on Low Activation Material, Culham, UK, 8-12 April 1991

"Shallow land burial is impractical and politically unsound. This is true in many European countries at present and will probably be true in the US soon. It should be dropped from consideration in definition of criteria for low activation materials."

The "Everything Goes Deep" Philosophy

Implication

"If deep geological disposal replaces shallow land burial, then there is a greatly reduced benefit of low activation over conventional materials."

"The emphasis may shift from long lived radioactivity to short term afterheat (safety) problems. Manganese, because of the high vapor pressure is not favored in this scenario."