Swelling in Potential CTR First Wall Materials

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The term dimensional stability is one which must be added to the designer's list of desirable qualities for CTR structural components. Previous experience in the LMFBR program[1] has shown that constriction of coolant channels, warping of extended structures, and premature failure are but a few of the problems generated by irradiation induced metal swelling. Therefore, it is vital that proper attention be paid to this phenomena in CTRs to avoid costly delays in the realization of economic fusion power.

The four main causes of irradiation induced metal swelling and the temperature regions of their importance are listed below:

1) Growth	$< 0.2\ T_m$*
2) Voids	$\sim 0.3 - 0.5\ T_m$
3) Bubbles	$\gtrsim 0.5\ T_m$
4) Transmutations	all temperatures

The first effect is due to the accumulation of isolated point defects such as vacancies.[2] It is not expected to be a serious problem for CTRs because current plans call for the first wall to operate in the neighborhood of ~ 0.3 to $0.5\ T_m$.

The second effect is due to the accumulation of irradiation produced vacancies into three dimensional cavities such as those shown in Figures 1a and 1b for metals of interest to CTR designers. These voids can cause considerable volume changes in metals and values of 10-15% have already been reported for stainless steel irradiated in the 100-200 dpa** range.[3] The universality of this effect is shown in the fact that in the 5 years since voids were first discovered[4] they have been found in

* T_m = absolute melting point

** dpa = displacement per atom

VOIDS PRODUCED BY 900 °C HEAVY ION BOMBARDMENT

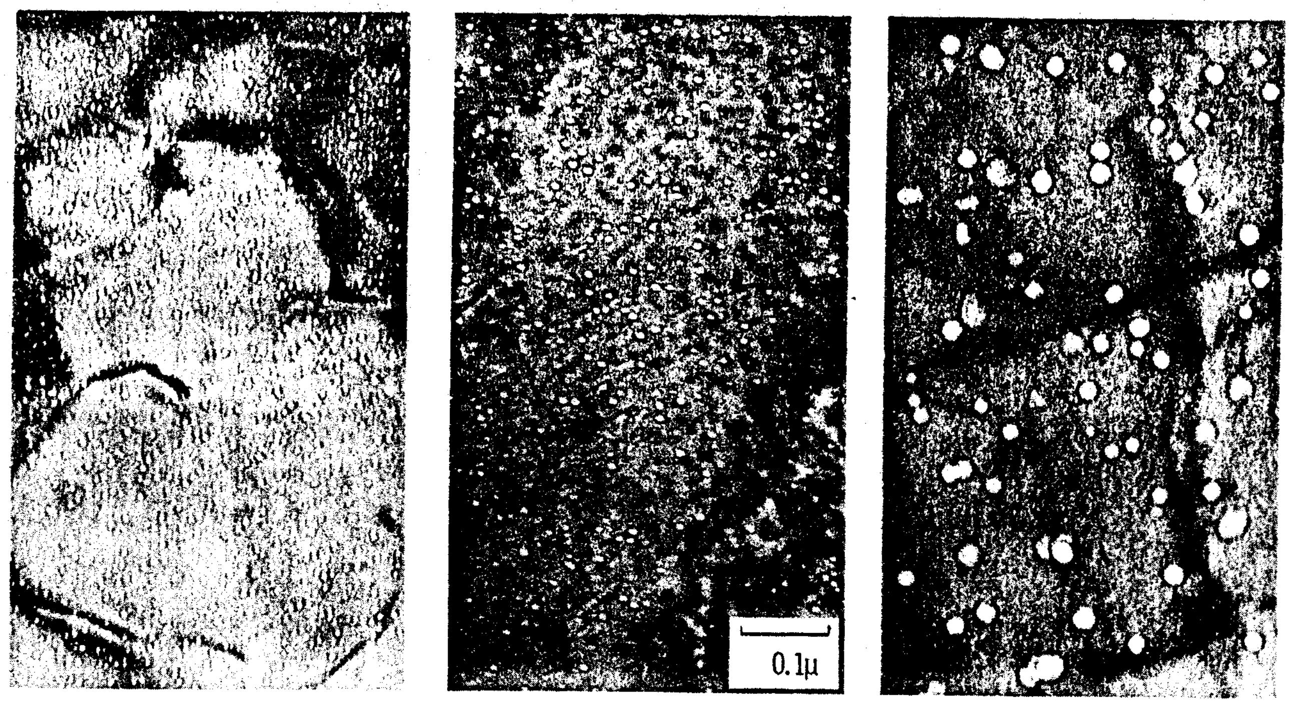

Figure 1a (GK)

VOIDS INDUCED BY 7.5 MeV TANTALUM BOMBARDMENT

TO ~30 dpa AT 800°C

Nb-1Zr

Vanadium

Figure 1b (GK)

thirteen pure metals (Ni, Pt, Al, Cu, V, Nb, Mo, Ta, W, Fe, Re, Co, and Mg) and in several alloys (304, 316, and 321 stainless steel, Incoloy-800, aluminum alloys 1100 and 8001, Mo-Ti and Mo-Ti-Zr-C systems, Nb-Zr and Cu-Al). There are a few notable exceptions to these observations and thus far no voids have been found in Ti, Zr, Au, and a V-20 Ti alloy even when irradiated under the "proper" temperature and fluence conditions. The reader is referred to references 5 and 6 for rather complete and up-to-date summaries of this field.

In addition to the deleterious effects of a uniform swelling, the effect of swelling gradients can be particularly troublesome. Such inhomogeneous swelling results from the fact that there are severe temperature and neutron flux gradients in nuclear systems and that the void size and number densities are very sensitive to these quantities. The resulting swelling gradients can produce warping of free standing components and severe stresses in those members which are held rigidly.[1]

What does this mean in terms of the refractory metals (V, Mo, Nb or their alloys) proposed for use at 600-1000°C in future CTRs? First of all, these temperatures are in the "proper" range for the formation of voids, i.e., 0.3-0.44 T_m for Mo, 0.32-0.48 T_m for Nb and 0.4-0.59 T_m for V. Secondly, the total damage resulting from a one week exposure to a 10 MW/m^2 wall loading ($\sim 4 \times 10^{-6}$ dpa/sec) is well in excess of that known to produce voids in the refractory metals. The highest neutron fluence reported to date[7] for refractory metals of interest is equivalent to 34 dpa for Nb and 36 dpa for Mo, less than 2% of the expected damage in a CTR first wall over a 20 year period. The swelling reported, even at these low damage levels, is 0.5-1%. Previous studies[8-10] have shown that the swelling increases as roughly the 3/2 power of the damage in Ni, Al, and stainless steel. Applying this dose dependence to the refractory metals would imply swelling values of well in excess of 100%, obviously an intolerable level.

There has been recent cause for optimism in this area because it has been shown that swelling does not increase indefinitely in such metals as Ni[8] and stainless steel.[3] The volume increase due to voids shows a saturation level at 10% or less for Ni and 10-15% for stainless steel. The cause for the saturation in Ni is felt to be the three dimensional ordering of the voids such that the voids are the predominant sink for both vacancies and interstitials. The reasons for saturation in stainless steel are unknown at this time.

The obvious hope is that the refractory metals will show similar saturations and there have indeed been reports of ordered voids in Mo,[7,11,12] Nb,[7,13] and Ta.[7] Figure 2 shows such ordering in Nb. It is too early to tell whether these void structures will also limit the swelling in refractory metals.

Another solution to the problem is to lower the wall loading by perhaps a factor of ten. The swelling values in this case will be comparable to those presently encountered (and handled) in fast test reactors.

The third cause of swelling has been treated in a detailed manner by Martin of the U.K.[13] Figure 3 shows the amount of swelling to be expected in Nb if all the helium produced by transmutation reactions for 20 years was collected into bubbles. The amount of swelling is most likely to be in the 1-10% range because the average bubble size is unlikely to exceed more than 1000 Å. However, it is felt that long before helium bubble swelling becomes a problem, the loss of ductility due to helium embrittlement will limit the useful lifetime of the vacuum wall.

The final cause of swelling, that due to the generation of foreign metallic elements by transmutations is treated by Wiffen at this meeting and will not be covered here.

In summary, the most serious dimensional instability problems will result from the formation of voids in refractory metals. The exact magnitude of the problem is unclear due to a lack of data and the possibility of a saturation in the swelling at high dpa values. The swelling problem can be alleviated by lowering the wall loading to 1 MW/m^2 or less, or by developing swelling resistant alloys which can retain their strength in the 600-1000°C range.

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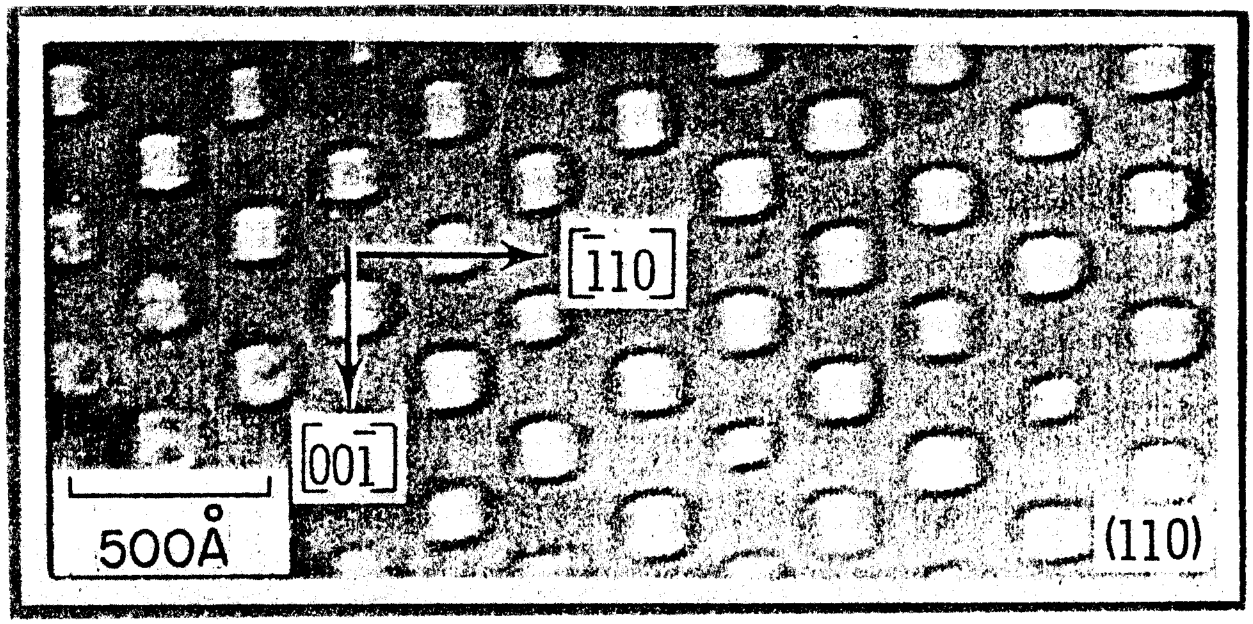
1. P. R. Huebotter and T. R. Bump, "Int. Conf. on Radiation Induced Voids in Metals," Albany, New York, June 1971.

2. R. O. Simmons and R. W. Balluffi, Phys. Rev. 120, 1229 (1958).

3. R. S. Nelson, "Int. Conf. on Radiation Induced Voids in Metals," Albany, New York, June 1971.

4. C. Cawthorne and E. J. Fulton, Nature 216, 575 (1967).

ORDERED VOIDS IN NIOBIUM BOMBARDED AT 800°C WITH 7.5 MeV Ta^{++} IONS



~140 dpa

Figure 2 (GK)

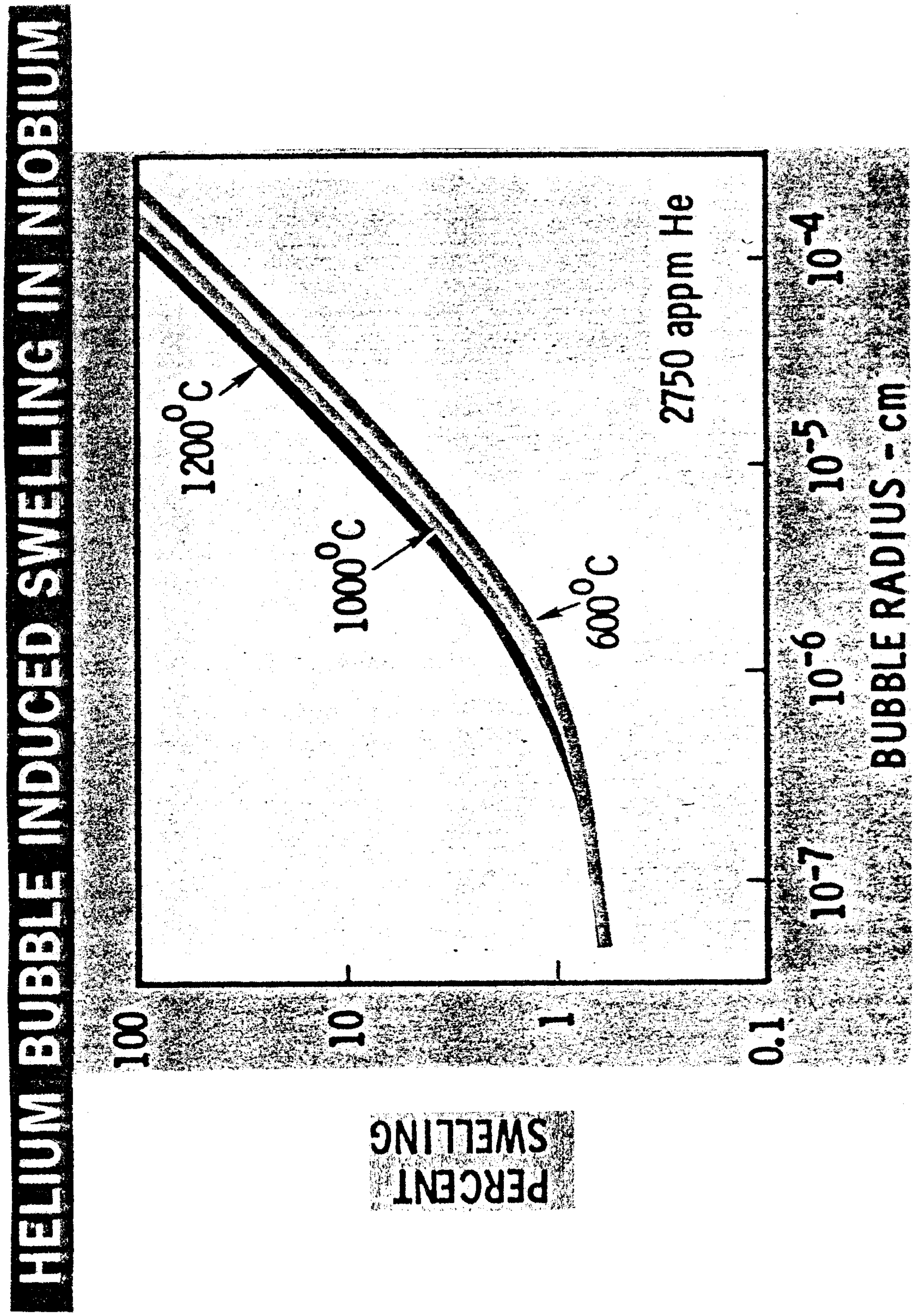

HELIUM BUBBLE INDUCED SWELLING IN NIOBIUM
PERCENT SWELLING
100
10
1
0.1
BUBBLE RADIUS - cm
10-7
10-6
10-5
10-4
1200°C
1000°C
600°C
2750 appm He

Figure 3 (GK)

5. "Int. Conf. on Radiation Induced Voids in Metals," Albany, N.Y., June 9-11, 1971.

6. "Conference on Voids Formed by Irradiation of Reactor Materials," Sponsored by the British Nuclear Energy Society, Reading, England, March 24-25, 1971.

7. F. W. Wiffen - reference 5.

8. G. L. Kulcinski, J. L. Brimhall and H. E. Kissinger, J. Nucl. Mat. 40, 166 (1971).

9. N. H. Packen, J. Nucl. Mat. 40, 1 (1971).

10. E. E. Bloom, ORNL-4580, August 1970.

11. J. H. Evans, AERE-R-6647, 1971.

12. G. L. Kulcinski and J. L. Brimhall, "Discussion Meeting on Defects in Refractory Metals," MOL, Belgium, September 20-22, 1971.

13. D. G. Martin, "Nuclear Fusion Reactors," UKAEA Culham Laboratory, September 1969.