Swelling Behavior of U-Pu-Zr Fuel

GERARD L. HOFMAN, R.G. PAHL, C.E. LAHM, and D.L. PORTER

Recent fast reactor driver fuel tests in the Experimental Breeder Reactor II (EBR-II) have demonstrated good performance of U-Pu-Zr fuel alloys to burnups >15 at. pct. Postirradiation examination of these tests has yielded a large amount of fuel-swelling data and metallographic information. These data show that prior to making contact with the cladding tube, metallic alloy fuel swells rapidly due to its high fission-enhanced creep rate and irradiation growth. Measurements of macroscopic fuel slug growth during the entire fuel pin lifetime can now be understood by properly taking into account the irradiation environment and microstructural changes for the various alloy compositions. It has been determined that fission rate, temperature, and plutonium concentrations influence the observed macroscopic swelling rate.

I. INTRODUCTION

SWELLING is probably the most universal problem encountered in the irradiation of nuclear fuels. The major swelling mechanism is basically the same for all types of fuel; it consists primarily of nucleation and growth of bubbles of the insoluble fission gases Xe and Kr. However, there are characteristic differences in the fuel behavior.

For example, oxide fuel has a unique swelling behavior at high temperature. Because of its low thermal conductivity, oxide fuel operates with relatively high radial thermal gradients. Migration of fission-gas bubbles in such a high thermal gradient results in nearly complete gas release and, therefore, little swelling. Ceramic fuels with high thermal conductivity, such as nitride, carbide, and metallic fuels, exhibit high fission-gas-induced swelling. This consists of the nucleation and growth of largely immobile intragranular fission-gas bubbles, and through diffusion of fission gas to grain boundaries, in relatively larger intergranular bubbles. At sufficient fissile burnup, intergranular bubbles link up and form paths for fission-gas release from the fuel. Depending on fuel properties and temperature, intragranular bubbles may eventually grow large enough to interconnect as well. At this point, a large amount of swelling has occurred, and therefore, a major fraction of the fission gas will be released from the fuel. Allowing a large amount of fuel swelling and gas release to take place reduces fuel-cladding mechanical interaction (FCMI), and is the key to successful high burnup operation of these fuels. This is achieved by employing relatively low planar smeared densities, typically around 75 pct. The large amount of radial swelling allowed by low planar smeared density also results in much larger axial growth of the fuel column. For example, sodium-bonded carbide[3] and sodium-bonded metallic U-Zr, both with a smeared density of ~75 pct, contact their cladding at ~16 pct diametral swelling, and interestingly, both fuels have at that point grown axially by approximately 10 pct. The anisotropic swelling behavior of these fuels is caused by a difference in swelling behavior between the inner and outer regions of the fuel. A higher swelling implies higher fission-gas diffusivity and higher creep rate in the central region of the fuel. As a result of a higher swelling rate and plastic, fluidlike behavior in the hotter central part of the fuel, this fuel is in a hydrostatic stress state, while the cooler and stronger outer shell is in a state of tensile stress. Under ideal conditions, *i.e.*, if the center is highly plastic and no axial temperature gradient exists, the circumferential tensile stress component in the outer zone is twice the axial component. In an actual fuel element, the ratio of circumferential and axial tensile stress in the outer shell may be somewhat less than two, because there will be a modest axial temperature gradient and the stress state in the central fuel zone may not be purely hydrostatic. However, it appears that in carbide, nitride, and metallic fuels that possess a plastic central region with high swelling characteristics, the circumferential tensile stress in the outer fuel zone is always larger than the axial tensile stress. The effect of these tensile stresses on swelling and creep in the outer fuel zone explains the larger radial than axial swelling and, thus, observed anisotropy.

In addition to this basic fission-gas-induced swelling mechanism, metallic fuels may exhibit additional anisotropic irradiation growth and swelling induced by the radiation response of noncubic crystalline phases present in uranium and plutonium and their alloys. Anisotropic irradiation growth and swelling of orthorhombic alpha uranium were first recognized in the late 1950's by Kittel and Pain[1] and were extensively studied in the 1960's. Shape changes involving (010) elongation and (100) shinkage are the result of anisotropic condensation of interstitial and vacancy loops in the lattice. The Burgers vectors of different loops align with the prevailing stresses in the vicinity of the fission spike where they are formed.[5] Thermal stresses are highly anisotropic because of the large anisotropy of thermal expansion in orthorhombic α-U.[2] As a result, crystallographically aligned microtears are formed in each grain. In α-U, these tears most likely nucleate at twin boundaries formed during the martensitic transformation.[4]

In polycrystalline fuel, mismatched growth stresses that develop at grain boundaries cause plastic flow or cavitation, depending on the grain size and temperature. Fission-gas diffusion to these grain-boundary cavities and to the intragranular microtears gradually transforms these initially empty features to fission-gas bubbles. Several

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factors may result in net anisotropic swelling of an alloy that undergoes tearing. The presence of a preferred grain orientation or texture, induced by stress or temperature gradients when the fuel undergoes transformation to the α phase during manufacture, has a direct effect on isotropy. Indirectly, however, the stress state in the fuel element noted above has a pronounced effect on tearing and cavitation, and thereby exacerbates the difference between radial and axial swelling of the fuel pin when α phase is present.

II. EXPERIMENTAL

The irradiation data discussed here were generated in an experimental program designed to develop fuel for the Integral Fast Reactor (IFR). The fuel elements consisted of metallic U-Zr and U-Pu-Zr alloy pins sealed in austenitic stainless steel cladding tubes. Irradiation was carried on in the EBR-II reactor to a heavy metal burnup of 15 at. pct. Examinations have been completed at 0.4, 0.9, 2, 3, 6, and 12 at. pct burnup.

The fuel pins were fabricated by injection casting into fused quartz molds. This process produces a homogeneous solid cylindrical fuel slug 34 cm in length. The fuel pins were then sealed in Type 316 and Type D9 (20 pct cold-worked) stainless steel tubes under an argon plenum atmosphere. The annulus between fuel slug and cladding tube was filled with sodium to ensure heat transfer. The fuel elements began irradiation in the as-cast condition. In this condition, the zirconium is largely in supersaturated α' U-Pu phase with the presence of a number of zirconium-base precipitates caused by small quantities of carbon and oxygen impurities. The irradiation and thermal environment created by fissioning of the fuel allows the fuel structure to revert to a more equilibrium-like mixture of phases.

The test elements were fabricated in two distinct groups, one consisting of fuel with 0, 3, 8, 19, 22, and 26 wt pct Pu-10 wt pct Zr-balance U, clad in 0.290-inch-diameter stainless steel tubes and the other consisting of 0, 8, and 19 wt pct Pu-10 wt pct Zr-balance U, clad in 0.230-inch-diameter tubes. The fuel linear power was similar for the two groups, resulting in a nominally lower temperature gradient and lower fission rate for the 0.290-inch-diameter element. Because of a higher coolant flow, overall temperature in the 0.290-inch-diameter elements was lower as well. In this paper, the 0.290- and 0.230-inch elements are referred to as A and B elements, respectively, to facilitate comparison. Nominal operating parameters for both groups are shown in Table I.

The overall swelling of the experimental fuel pins was determined by measuring diameter and length changes from neutron radiographs taken at various intermediate burnup intervals. This technique gave reliable data on free swelling up to the point at which the fuel contacts the cladding. Beyond this point, swelling is mechanically restrained by the cladding, and only axial fuel strain can be measured. The radiography measurements were compared with measurements from metallographic sections taken from selected fuel elements. This was found to be an accurate experimental technique for measuring axial swelling but gave generally somewhat higher values for diametral swelling. However, the diameter measurements do accurately represent the relative difference between the various fuel compositions and the axial diameter profiles. The fuel microstructure was studied with standard metallographic techniques and scanning electron microscopy (SEM) employing secondary electron (SE) and backscattered electron (BSE) detection.

Table I. Comparison of U-19Pu-10Zr 0.230- and 0.290-Inch Elements Nominal Fuel Operating Conditions (at Beginning of Life)

Cladding diameter, in.	0.230	0.290
Fuel slug diameter, in.	0.171	0.223
Pin power, kW/ft	12.5	12.5
Peak fuel centerline temperature, °C	610	610
Radial fuel ΔT, °C	130	130
Radial fuel temperature gradient, °C/in.	1520	1160
Peak U^{235} fission rate, 10^{13} fissions/cm$^3 \cdot$ s	8.8	4.5

III. FUEL PIN SWELLING MEASUREMENTS

Fuel pin length changes for various fuel compositions as a function of burnup in the A elements are shown in Figure 1. Because these length changes were measured at frequent intervals from neutron radiographs taken from the same set of elements, they offer the most detailed picture of *overall* fuel swelling at low burnup. The swelling of all compositions has an incubation burnup of approximately 0.3 at. pct followed by rapid swelling over approximately a 1 at. pct burnup interval. All compositions behave in a similar manner, with the exception of 0 pct Pu, which swells significantly faster and reaches a somewhat higher level of axial growth.

The leveling off of the swelling *vs* burnup curve is due to axial shear stresses caused by fuel-cladding contact; however, as noted earlier for isotropic swelling, this level should be reached at ~16 pct for an as-built planar smeared density of 75 pct, not as shown in Figure 1 at 6 to 9 pct! This anisotropic swelling behavior is shown

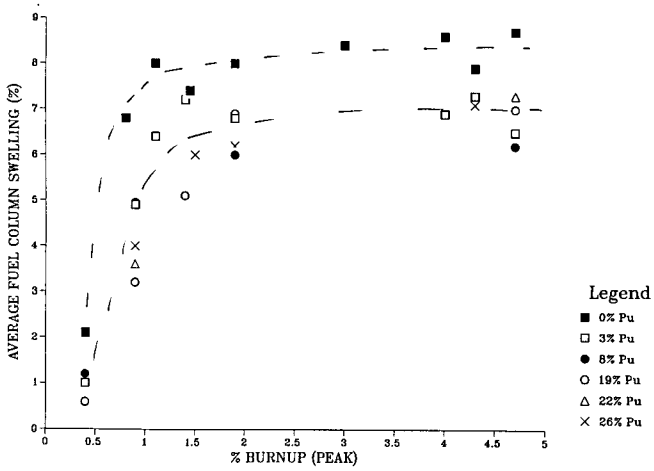


Fig. 1—Axial fuel swelling of 0.290-in. elements.

graphically in Figure 2, where both average axial and diametral swelling measurements taken at two burnup intervals prior to fuel-cladding contact are illustrated. The degree of anisotropy varies substantially between the different fuel compositions.

The B elements were first examined at ~1 at. pct burnup and, at that point, had already reached fuel-cladding contact. Therefore, diameter data are not available for this set of elements. However, axial swelling measurements were continued well beyond 1 at. pct burnup, after which fuel-cladding contact is made and swelling slows dramatically. These axial swelling data are shown in comparison with the A data in Figure 3 for fuel composition common to the two sets of elements. The behaviors of 0 pct Pu and 8 pct Pu are virtually identical for the two tests that ran incidently under different irradiation conditions (Section II). However, the axial swelling in 19Pu B elements is only about 1/3 as much as that in A elements. It would appear that the B elements swelled very anisotropically, for at the point of fuel-cladding contact (~1 at. pct burnup), the axial swelling is only ~3 pct compared to a would-be isotropic value of 16 pct!

IV. FUEL MICROSTRUCTURE

In the injection casting technique employed in fabricating the fuel pins, the fuel alloys cool rapidly, leaving little time for diffusion. The initial microstructure of all fuel compositions consists essentially of a metastable low-temperature α phase that is supersaturated in Zr and forms martensitically, the so-called α' phase. One or two dispersed phases of Zr (O, N, C) and sometimes Si are always present in various quantities depending on minor variations in melting and casting parameters. These Zr phases are very stable, and their sole effect on fuel behavior is that they remove some Zr from the bulk fuel alloy.

When the fuel pin is brought to temperature in the reactor, the fuel transforms, by diffusion, to its equilibrium phase structure according to the equilibrium phase diagrams for U-Zr and U-Pu-Zr shown in Figures 4 and 5. It is important to note that during irradiation, the equilibrium phase structure changes because the very formation of cavities, tears, and gas bubbles decreases the thermal conductivity of the fuel. This increases its temperature even when power and coolant flow are assumed to remain constant.

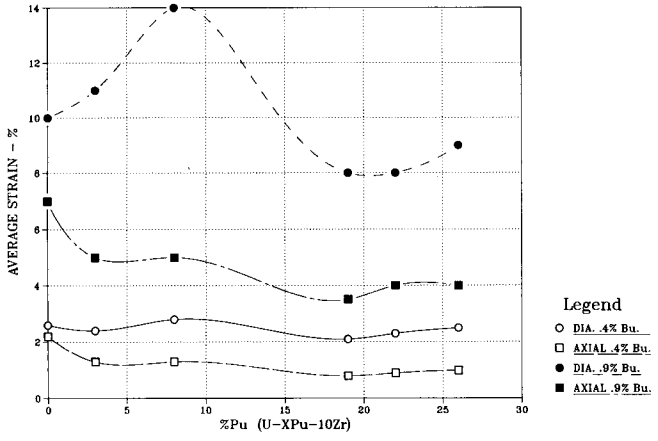


Fig. 2—Axial and average diametral fuel swelling of various 0.290-in. elements.

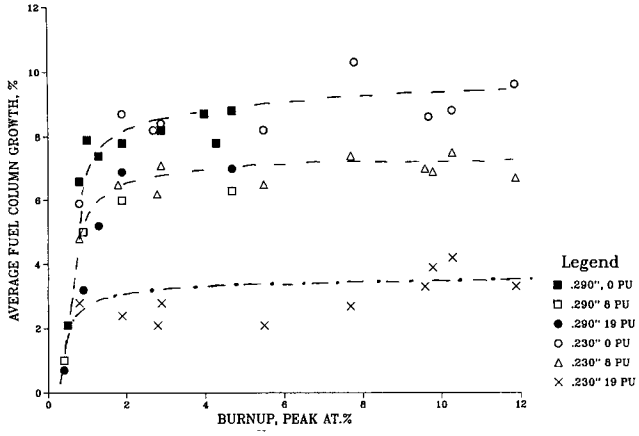


Fig. 3—Axial fuel swelling in 0.230- and 0.290-in. diameter elements

A. *U-Zr*

The microstructural development of the binary alloy with increasing burnup is less complex because the number of possible phases is less than in a ternary alloy. At the beginning of irradiation, most of the fuel in both the A and B tests is in the $\alpha + \delta$ phase field with only the

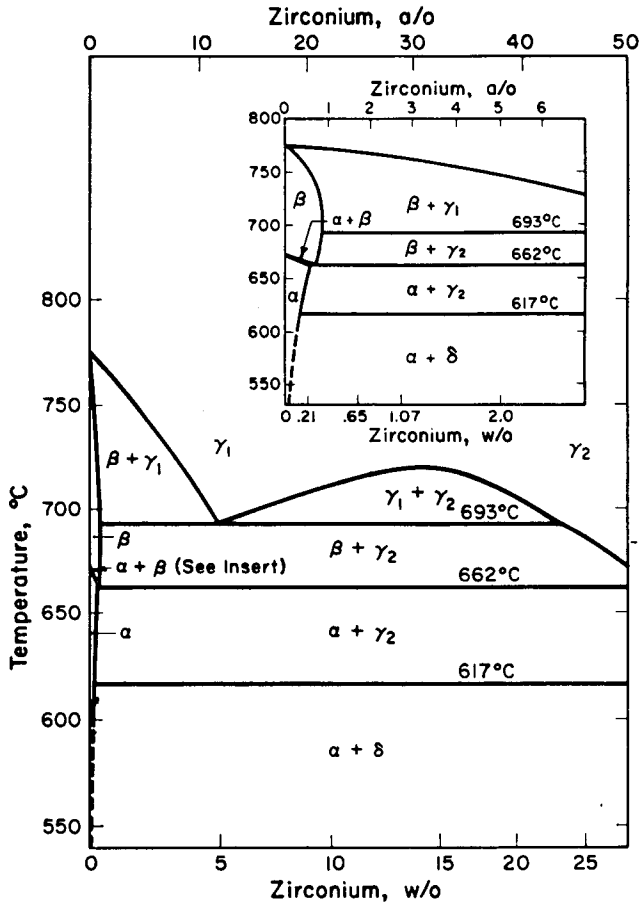


Fig. 4—U-Zr phase diagram.

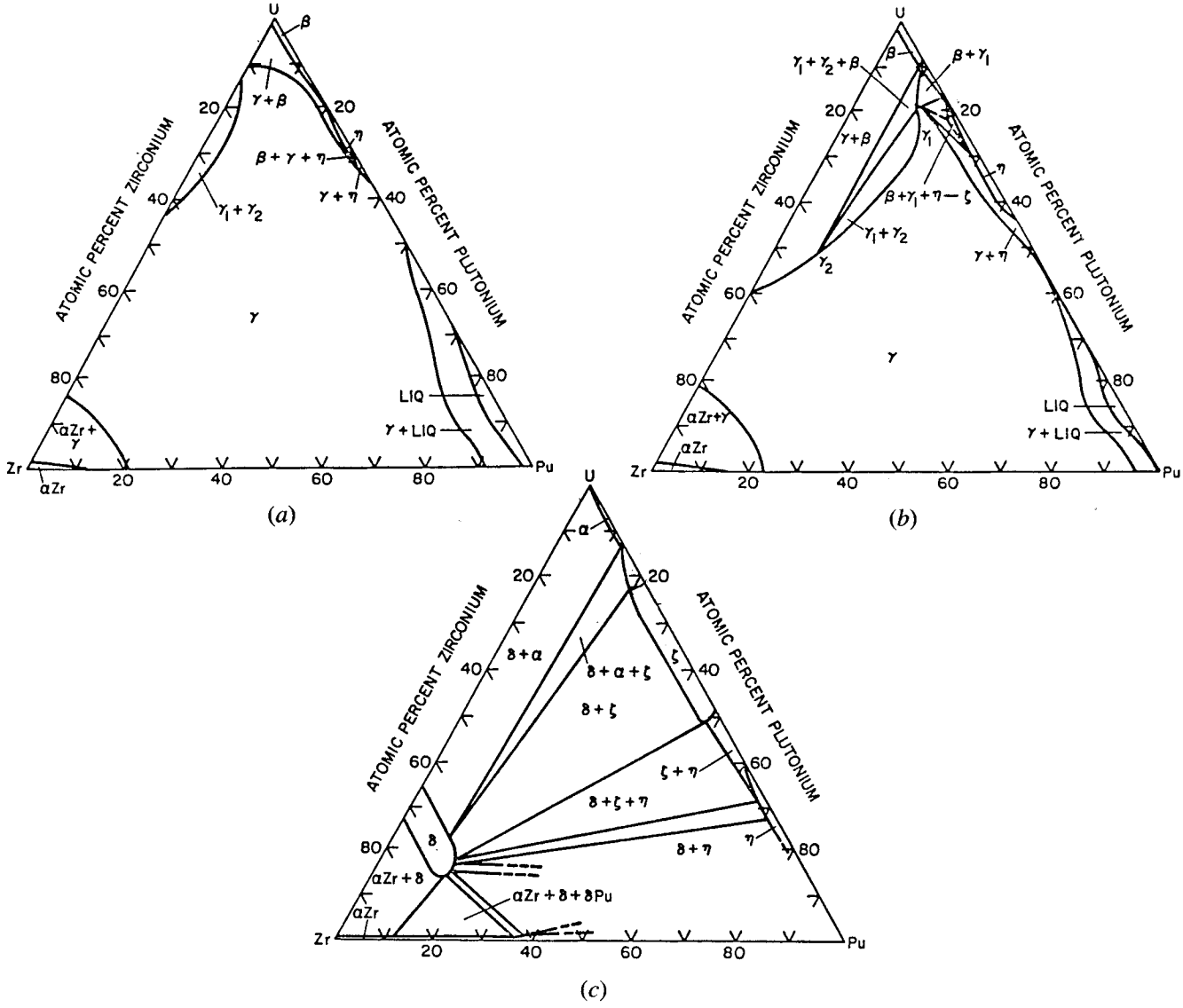


Fig. 5—Isothermal in U-Pu-Zr phase diagram: (*a*) 700 °C, (*b*) 670 °C, and (*c*) 500 °C.

hottest part of the fuel in the high-temperature $\gamma_1 + \gamma_2$ or γ field (Figures 4 and 5). The morphology of the equilibrium phases in U-Zr depends strongly on heat treatment. In the present irradiation, this consists of long-term annealing of the as-cast α' phase in a temperature gradient. The fuel develops a two-phase structure similar to that found out-of-pile.

Below 662 °C, the orthorhombic α phase forms the matrix of the alloy, δ lamellae are present below 617 °C, and γ_2 lamellae are present between 617 °C and 662 °C. Above 662 °C, the cubic γ phases form the matrix. The differences in swelling behavior of these phases give the fuel its distinct concentric porosity patterns, shown in Figure 9.

Porosity development during the low burnup swelling stage, *i.e.*, before fuel-cladding contact, in a U-10Zr A element is shown in Figure 6. The center temperature of the fuel is below 660 °C, and the transverse cross section consists of two concentric zones, *i.e.*, $\alpha + \delta$ toward the surface and $\alpha + \gamma_2$ at the center. As can be seen in Figure 6, the only discernible porosity appears to be grain-boundary tears. The two-phase microstructure near the surface is extremely fine, and there are possibly some small pores associated with the dark gray δ phase. The two-phase microstructure at the center is coarser, and in addition to grain-boundary tears, there is clearly a large fraction of pores forming on the dark gray (presumably γ_2) lamellae shown in Figure 7 at higher magnification. Thus, the center of the fuel pin is swelling at a higher rate than the outer zone and could therefore exert a stress on the outer zone. It seems plausible that relaxation of this stress by radial growth in the outer zone is a major component in the observed anisotropic fuel swelling. A third structural zone consisting primarily of the cubic γ phase occurs at the center of fuel pins that operate at centerline temperatures over 662 °C. These temperatures can be reached at the beginning of life in fuel operating at high power, or as in the present test pins, at moderate powers after a certain amount of porosity has decreased the thermal conductivity of the fuel. Figure 8 shows the phase structure and gas bubble morphology at the center of the U-10Zr element at 3 at. pct burnup. There is no

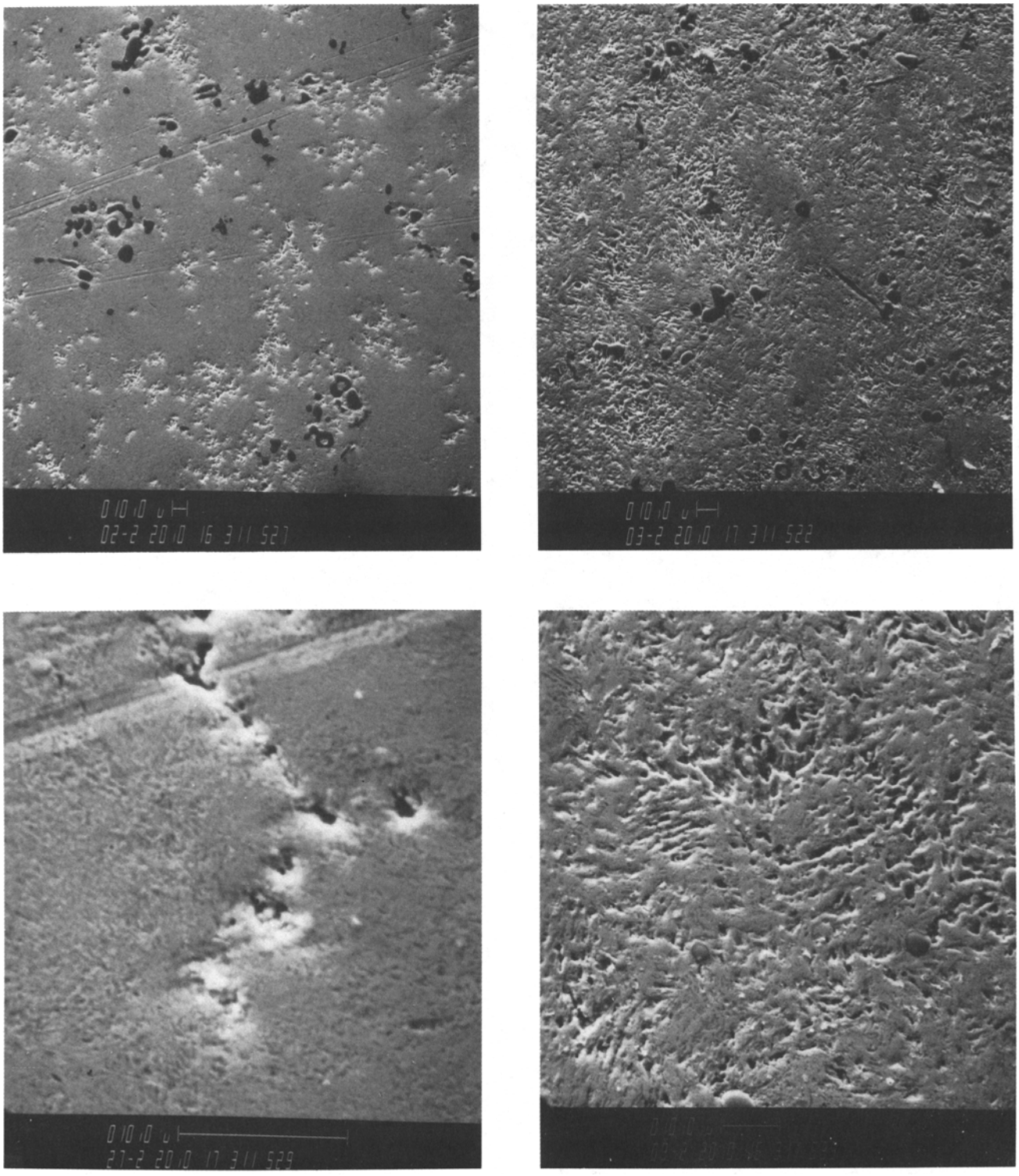


Fig. 6—Porosity development in U-10Zr fuel at ~0.8 at. pct burnup [right, hot center of pin and, left, cooler fuel toward pin surface (SEM, SE)].

evidence of tearing in the zone, and the large interconnected gas bubbles indicate high fission-gas mobility and high plasticity in the fuel. The light phase in Figure 8 is very low in Zr, representing the β phase at operating temperature, while the Zr content of the continuous gray phase corresponds to that of γ_2. It appears that the γ_2 phase determines the fission-gas bubbles behavior, and it seems reasonable to assume that at even higher temperatures, in the pure γ phase field, fission-gas bubble growth would be similar to that shown in Figure 8. In summary, the swelling behavior of U-10Zr fuel can be partitioned into two major microstructural zones. The swelling in the highest temperature zone, where γ phases form the matrix, is characterized by growth of large

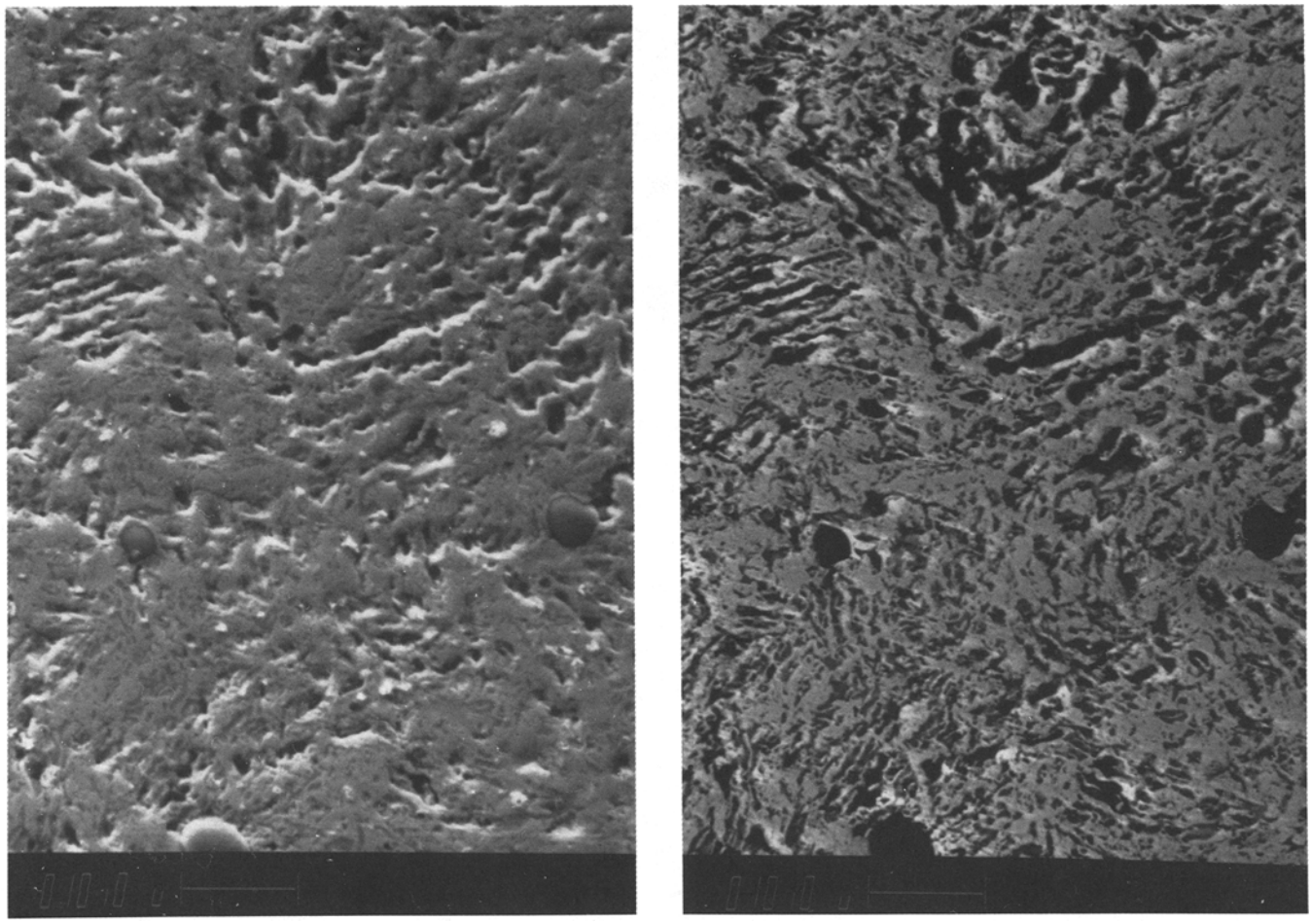


Fig. 7—Example of grain-boundary tears joint by porosity development at boundaries between lamellae high-Zr phase (dark) and low-Zr phase (light), left; SE, right; BSE, SEM.

fission-gas bubbles and is basically isotropic. At low temperatures, where the α phase is predominant, swelling at least initially consists of grain-boundary tearing. This swelling mode can be highly anisotropic as a result of imposed stresses and possible preferred orientation induced in the α grain structure.

An intermediate mixed-phase zone consisting of both α and γ_2 swells by both tearing at the α grain boundaries and fission-gas bubble growth in the lamellar γ_2 phase. The porosity structure in a transverse cross section of a fuel pin that operates with its center in the γ phase fields has a typically distinct "three-zone" appearance, as shown in Figure 9.

Thus, the observed swelling anisotropy in the fuel pins is a result of radial stresses deriving from higher swelling rates in the hotter internal microstructural zones that develop in a large radial temperature gradient in the fuel pin. Response of the inherently anisotropic α phase in the colder outer zones enhances radial swelling and thereby overall anisotropy.

B. *U-Pu-Zr*

The equilibrium phases in low-Pu ternary fuel alloys ($\leq$8 wt pct Pu) are basically similar to those of the U-Zr system (Figure 5). The addition of Pu, however, does alter phase transition temperatures and properties such as fission-gas diffusivity and plasticity of the fuel. These property changes may be responsible for increased swelling, which is reflected in the coarser porosity observed in these alloys (Figure 10). An increased swelling rate of the different radial structural zones, and, in particular, the effect of the generated stress on swelling, creep, and tearing in the outer region of the fuel zones, would explain the increase in diametral strain (anisotropy) found in the 3 and 8 pct Pu alloys (Figures 2 and 3).

The subsequent drop in anisotropy at higher Pu alloys (19 pct and above) would result from the absence of significant amounts of α phase in these alloys, a phase, as we have argued, that is highly susceptible to stress-induced anisotropic swelling. The result of these two competing effects, *i.e.*, increased swelling due to high Pu content and the shift of α stability to lower temperatures, is seen in Figure 11. Even the low-Pu fuel shows a swelling decrease at the higher temperature where α is absent. The swelling in the highest Pu alloy, which contains virtually no α phase (and therefore lacks an important contribution to anisotropy from this phase) exhibits an apparent temperature dependence indicative of a singular swelling mode found in many materials.

As mentioned before, the microstructe and swelling behavior of the 19 pct Pu B elements are very different from all other elements. In this set of elements, the axial swelling and the axial-to-radial swelling ratio are very

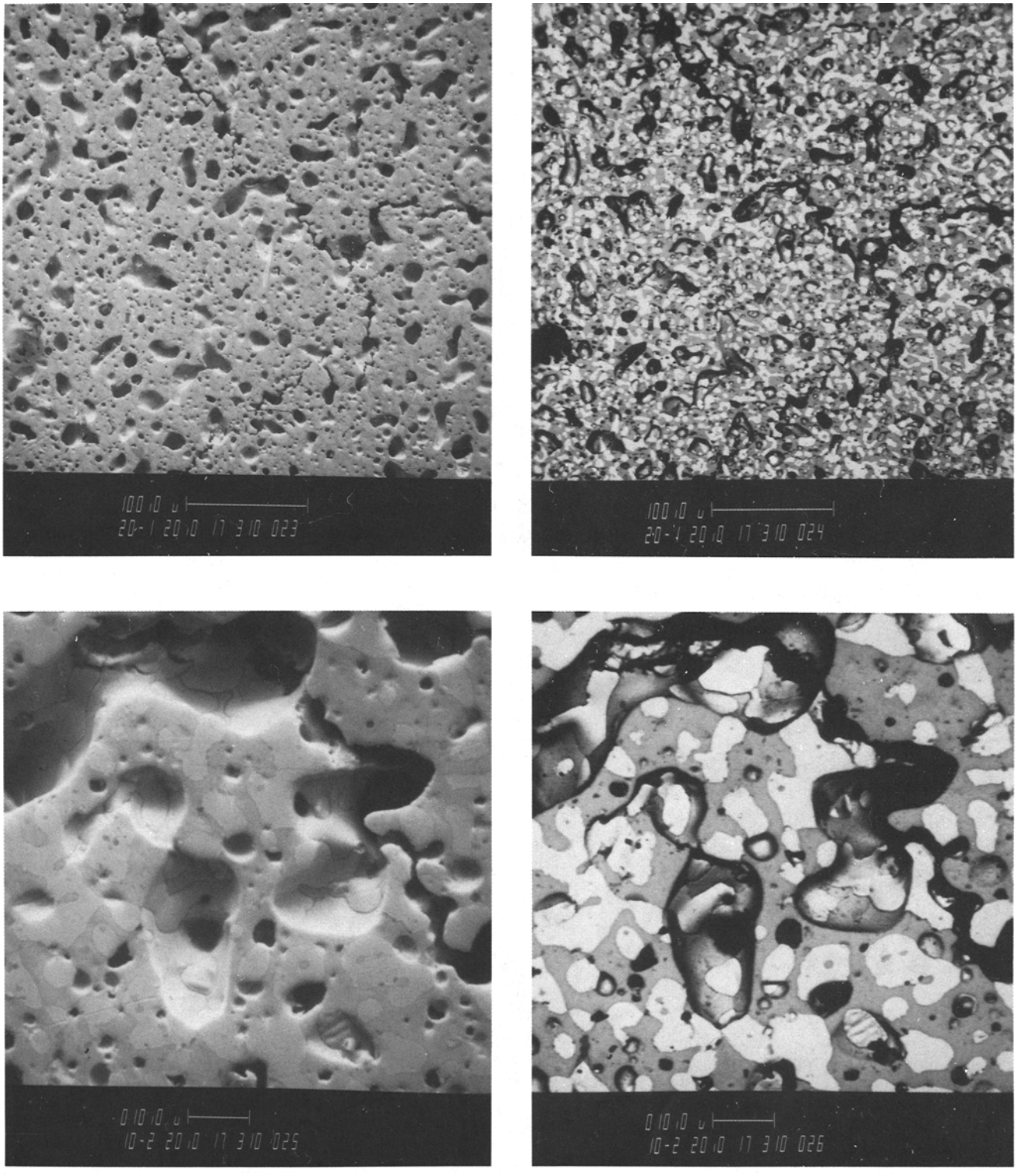


Fig. 8—Gas bubble morphology in high-temperature γ phase at center of U-10Zr element at 3 at. pct burnup (SEM; left, SE; right, BSE).

much lower than in the other fuel compositions, indicating a much higher degree of anisotropy (Figure 3). This larger anisotropic swelling coincides with cracking of the peripheral zone and pronounced radial redistribution of U and Zr early in the irradiation (Figure 12). Redistribution, or radial migration, of U and Zr appears to be a function of Pu content; it does not occur in the binary alloy and only to a minor degree in the 8 pct Pu alloys.

Redistribution of U and Zr in the A elements is observed only after higher burnup, *i.e.*, long after fuel-cladding contact takes place and, therefore, after free

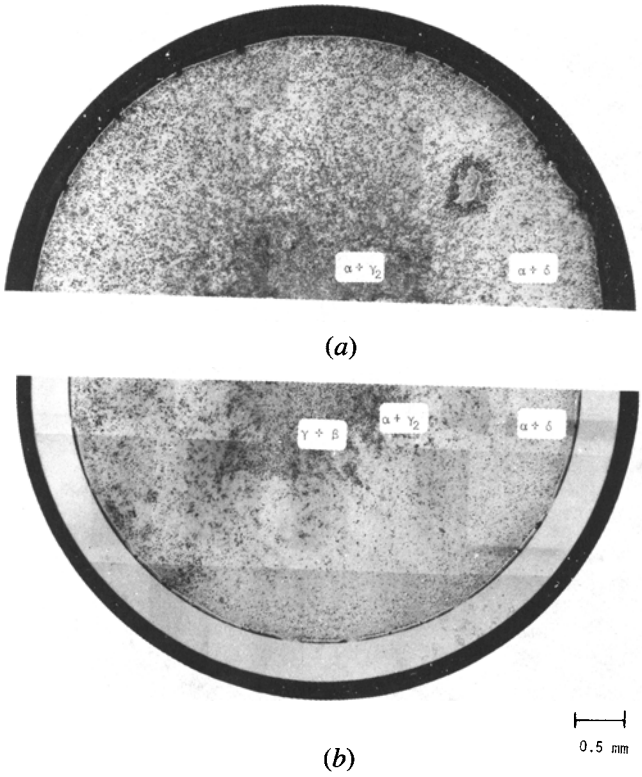


Fig. 9—(*a*) Microstructure of U-10Zr fuel at 0.9 at. pct burnup (cladding removed). (*b*) Microstructure of U-10Zr fuel at 6 at. pct burnup.

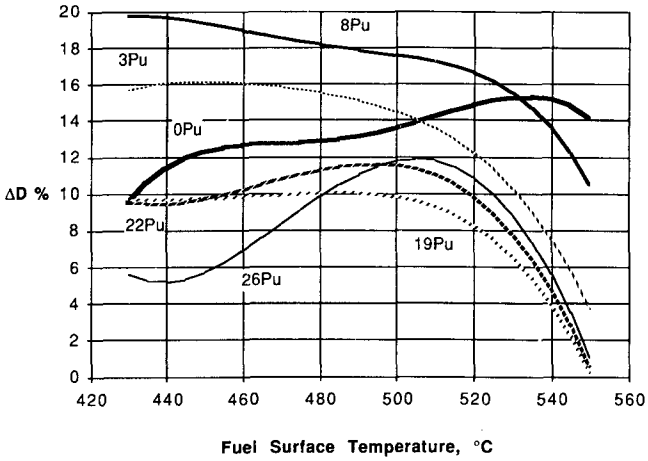


Fig. 11—Diametral swelling of 0.290-in. elements at 0.9 at. pct burnup.

swelling has ceased. The significant difference between the B 19 pct Pu fuel elements and the other elements is that redistribution in the former is observed at 1 at. pct burnup, *i.e.*, during the initial stage of free swelling, before fuel-cladding contact is made. It seems plausible to assume that this relatively rapid redistribution during the free-swelling stage has an effect on the anisotropy of the swelling.

Thus, in elements undergoing redistribution, one has, in addition to the distinctly different isotropically swelling high-temperature γ phase and the anisotropically swelling α phase, an intermediate third zone consisting of low-Zr phases. This intermediate zone has its own swelling behavior, characterized by the formation of a

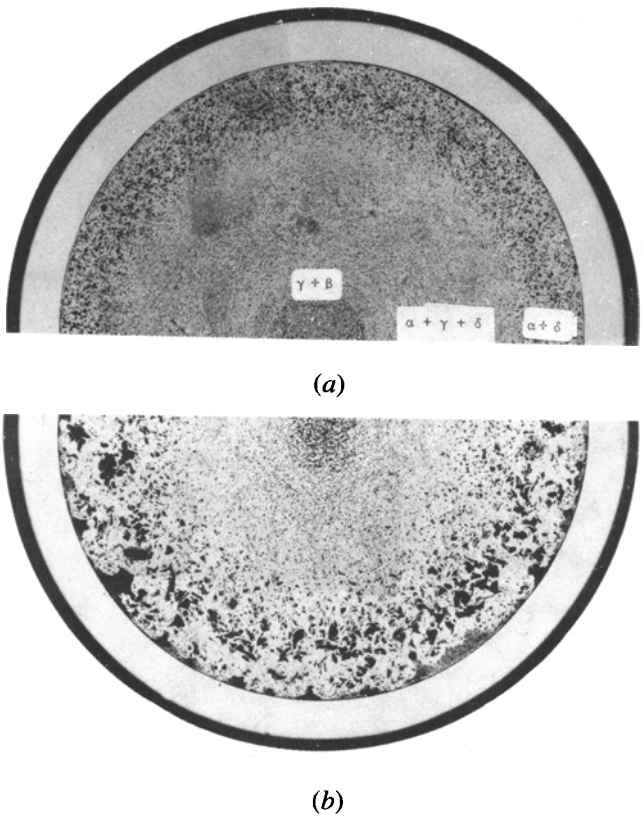


Fig. 10—(*a*) Microstructure of U-8Pu-10Zr fuel at 2 at. pct burnup. (*b*) Microstructure of U-8Pu-10Zr fuel at 10 at. pct burnup.

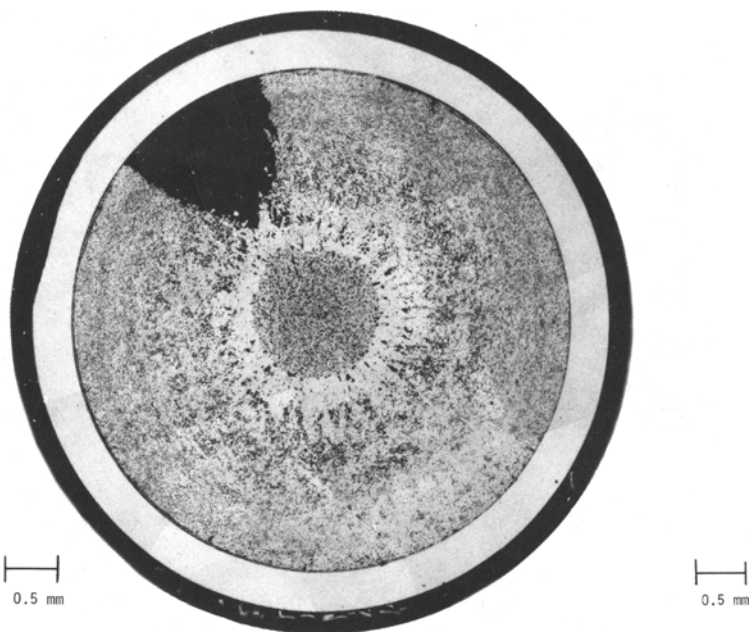


Fig. 12—Cross section of 0.230, 19 pct Pu element at 2 at. pct burnup showing zone formation due to Zr redistribution and cracking of peripheral zone.

high density of very small, rather regularly spaced bubbles, as shown in Figures 13 and 14.

Although detailed description of alloy component redistribution and phasal zone formation in fuels is beyond the scope of this paper, and is the subject of a separate study currently in progress, one explanation for redistribution in these elements is that it is caused by the diffusional flux driven by chemical potential differences and/or direct thermotransport in the radial temperature gradient.

A net flux of any of the components in a multicomponent alloy, which is needed to yield redistribution and phasal zone formation, depends on the magnitude of the thermodynamic forces acting on each component and on their mobilities. A plausible explanation of the early redistribution of Zr and U in the high-Pu B elements is that diffusional mobilities and driving forces in these elements are larger than in any of the other elements. Let us recall that there is no significant redistribution in U-Zr and low-Pu elements and that redistribution in the high-Pu A elements occurs at higher burnup after fuel-cladding contact has taken place. This late redistribution and zone formation, therefore, does not affect the free swelling of the fuel. Only the high-Pu B elements exhibit early redistribution during the free-swelling phase. High Pu content might result in larger mobility and larger heat of transport. As a result of higher power density, fission-enhanced diffusion and grad (T) are also larger quantities in the B elements. The rapid redistribution and zone formation in the B elements may generate significantly

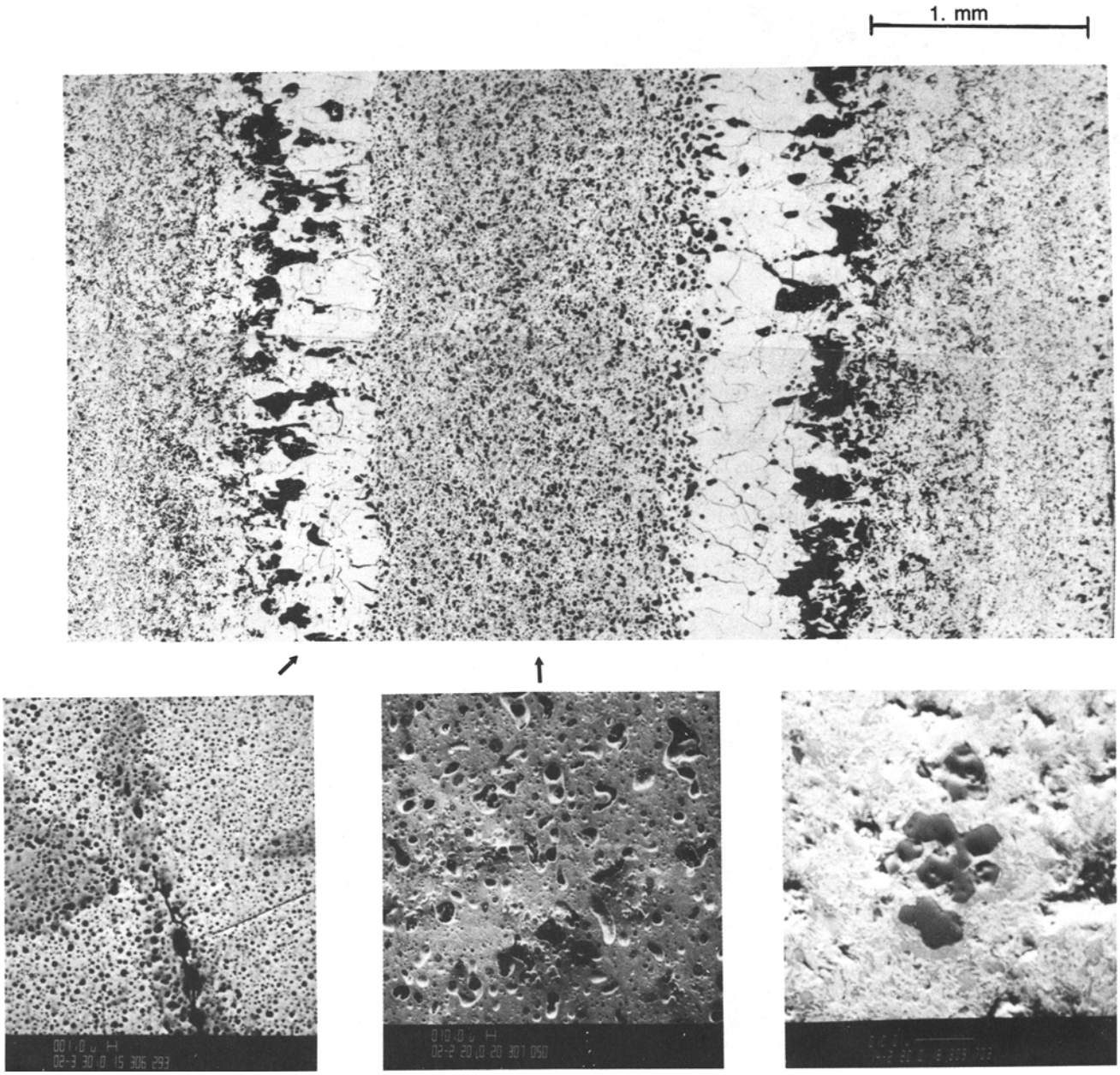


Fig. 13—Redistribution and zone formation in U-19Pu-10Zr fuel at 3 at. pct burnup; axial, optical metallographic section, and SEM details of zone microstructures.

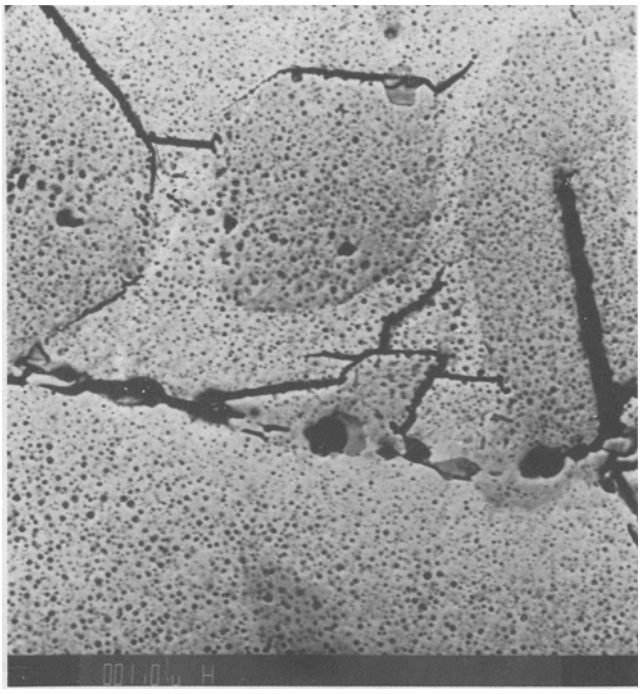


Fig. 14—Gas bubble morphology in intermediate, low-Zr, zone of U-19Pu-10Zr fuel at 3 at. pct burnup (SEM, BSE).

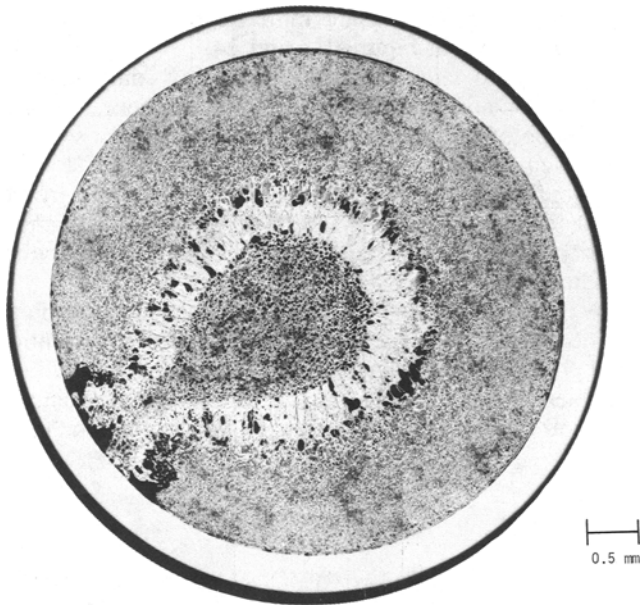


Fig. 15—Cross section of 0.230, 19 pct Pu element at 2 at. pct burnup showing extrusion of inner zone fuel into radial crack.

higher radial and azimuthal stresses in the fuel pin because of increased differences in thermal-physical properties and swelling behavior of the radial zones. The overall effect is a more rapid radial swelling, earlier fuel-cladding contact, reduced axial swelling, and hence large anisotropy. The microstructural state leading to early fuel-cladding contact in these fuel elements, *viz.*, high Pu operating at high grad (T) and high fission rate, is shown in Figure 12. The outer, anisotropic swelling zone has developed large radial cracks, presumably because there is insufficient time to relax radial stresses by means of creep. Cracking of the peripheral zone constitutes a nearly instantaneous diameter increase, thereby further shortening time to fuel-cladding contact and decreasing the ratio of axial-to-radial strain. That these stresses may indeed be the result of high-swelling inner zones of the fuel appears to be supported by the extrusion of this fuel into the radial cracks, as shown in Figure 15.

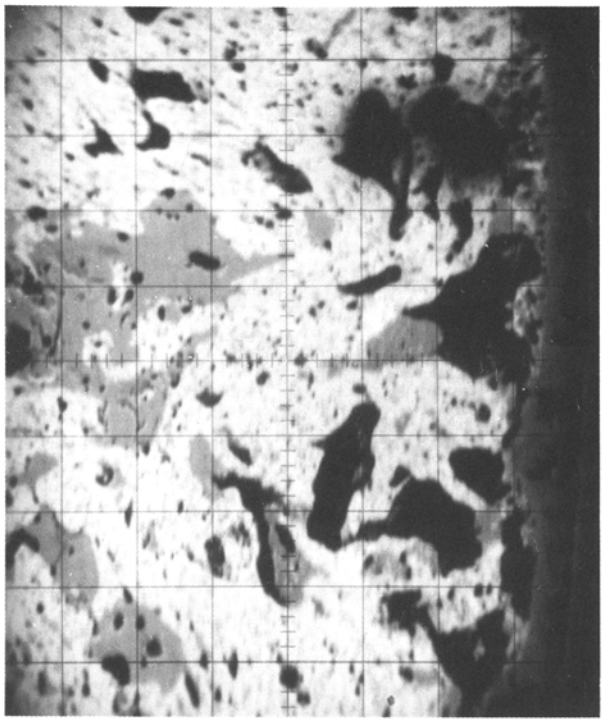
Incidentally, it has been shown that U-Pu alloys become very brittle in the temperature range at which the outer fuel zone operates.[6] Cracking may then be a sensitive function of temperature as well as the rate of stress gradient development. There is another distinct feature in fuel undergoing early radial redistribution and zone formation. We are referring to the rings of large porosity at the boundaries of the various zones. It is possible that this porosity is initially formed as a result of large discontinuities in the net vacancy flow occurring during redistribution and that this porosity is eventually stabilized by acquiring fission gas.

Finally, at high burnup, there is a significant contribution of nongaseous fission products to fuel swelling. The behavior of these fission products fall roughly into three separate groups, *viz*: (1) sodium solubles (chiefly Cs) that end up in the bond sodium above the fuel column and in sodium-logged pores, (2) most solid metallic elements that either dissolve in the fuel alloy or form compound precipitates in the fuel alloy matrix, and (3) rare earth elements (chiefly Ce, Nd, Pr, and La) that migrate to the periphery of the fuel pin, where they precipitate as a separate phase in existing pores (Figure 16). The sodium solubles then do not contribute to swelling. The fuel solubles, however, decrease the fuel alloy density, while the rare earth elements contribute to swelling by filling fission-gas pores.

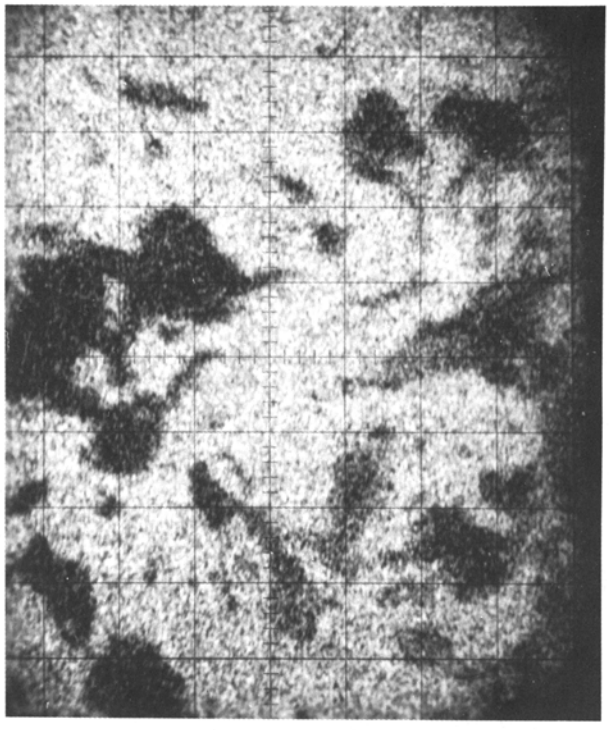
V. CONCLUSIONS

Swelling of U-Zr and U-Pu-Zr fast reactor fuel was found to be rapid and anisotropic prior to fuel-cladding contact. Fuel-cladding contact takes place at a low fissile burnup of approximately 1 at. pct. Beyond this burnup level, the fuel-swelling rate decreases drastically, as it is henceforth controlled by cladding deformation.

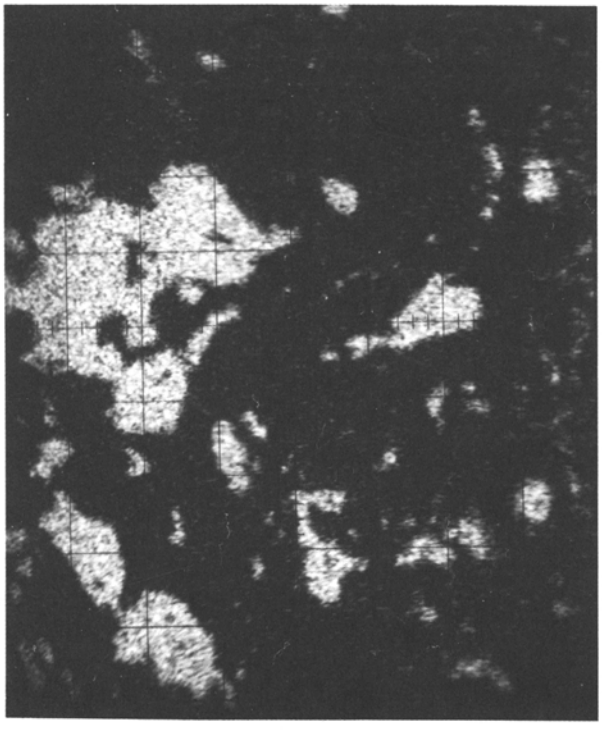
Anisotropy of the swelling, *i.e.*, the consistently higher radial than axial swelling component, is essentially due to the effect of differences in swelling mechanisms between the hotter and cooler part of the fuel. Specifically, the large radial temperature gradient leads to the development of distinct microstructural radial zones that have different swelling properties and thus interact mechanically. Addition of Pu increases the differences in swelling properties of the zones and their interaction, leading to a higher degree of anisotropy. However, the absence of the orthorhombic α phase, in the cooler regions of high-Pu fuel, in turn *reduces anisotropy*. This trend appears not to hold for high-Pu alloys operating at high temperature and fission rates, for these elements exhibit the lowest axial-to-radial strain ratio. In these alloys, radial redistribution of Zr and U occurs *early* in the irradiation, leading to the formation of three, rather than



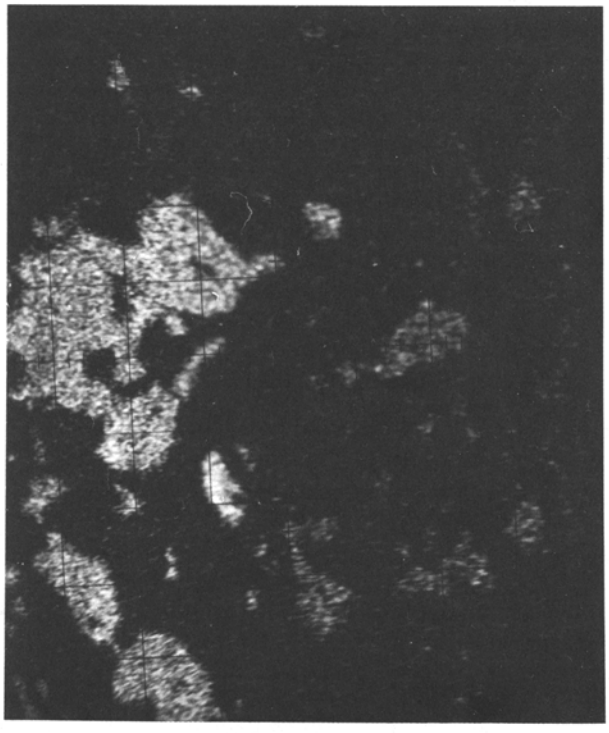
Specimen Current



U x-ray map



Nd x-ray map



Ce x-ray map

Fig. 16—Electron microprobe images of periphery of U-19Pu-10Zr fuel pin at 6 at. pct burnup showing presence of low-density phase consisting of rare earth elements in pores.

two, distinctly different radial microstructural zones. The large diffusional fluxes during redistribution and the differences in properties of the three resulting zones apparently increase the radial stresses and result in cracking of the cooler outer zone in the fuel. The overall result is much larger radial than axial strain of alloys undergoing zone formation *during* the free-swelling stage, *i.e.*, prior to fuel-cladding contact.

This paper links swelling behavior of the various alloys tested with the microstructural changes taking place during irradiation and is only descriptive in scope. A detailed evaluation of all of the aspects of the swelling problem, with the aim of obtaining equations for use in fuel element modeling and design, is in progress. Such an evaluation needs, in addition to the characterization of the swelling behavior of the various structural phases occurring in the alloys, a more precise determination of the thermal, physical, and mechanical properties of the fuel as it undergoes these structural changes and develops the various porosity morphologies. Essential also is the development of a diffusion model for the alloy redistribution.

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REFERENCES

1. J.H. Kittel and S.H. Pain: *Proc. 2nd Int. Conf. on the Peaceful Uses of Atomic Energy*, Genève, Switzerland, 1958, vol. 5, pp. 500-09.
2. S.N. Buckley: *Properties of Reactor Materials and the Effects of Radiation Damage*, D.J. Littler, ed., Butterworth's, London, 1962, pp. 413-16.
3. M. Colin: *Nucl. Technol.*, 1983, vol. 63, pp. 442-60.
4. R.D. Legget, B. Martel, and T.K. Bierlein: *Irradiation Behavior of High Purity Uranium*, Hanford Laboratory, Richland, WA, Report HW-79559, 1963.
5. S.N. Buckley: AERE Report R-5262, 1966, pp. 51-54.
6. J. Coffinberry: *The Metal Plutonium*, University of Chicago Press, Chicago, IL, 1961, pp. 120-21.