ventional distillation to be the cheapest and simplest process to apply. Reconcentration plant cost for this process is quite low—between $400,000 and $700,000 for our capacity requirement—depending upon whether packed or tray type fractionating towers are selected. Reconcentration plant capacity for the SSCR is a maximum of 400 lb of fluid/hr.

2. H_2O–D_2O is used only for gradual lifetime reactivity control, and hence no rapid reconcentration processes are required. Control rods are used in the SSCR for temperature defect, Doppler, and safety shutdown. These rods will be completely withdrawn at full power. (A slight adjustment can also be made in D_2O concentration to permit full Doppler withdrawal at lower powers, if desired.)

3. Capital and operating unit electrical costs for the SSCR reconcentration plant are low. For a 320 Mw(e) SSCR the capital equipment charge is 0.025 to 0.044 mills/kw-hr, and operation approximately 0.024 mills/kw-hr. These charges are even less for our current 400 Mw(e) plant. The use of this method of reactivity control affords economic advantages which far outweigh these small capital and operating costs.

To summarize, so long as reconcentration requirements for a variable H_2O–D_2O ratio reactor plant do not encompass *either* the lower concentration range (0.015% D_2O to 1% D_2O) or upper concentration range (99% to 99.99%), both capital and operating costs for the associated reconcentration plant will tend to be low.

Our studies indicate that Mr. Bebbington is correct in his statements concerning the relative costs of D_2O *production*. I would like to point out, however, that the control of a nuclear reactor by variation in H_2O–D_2O ratio is not only feasible, but can be made quite practical with respect to D_2O reconcentration plant requirements. One need only recognize and take into account all of the cost and other limitations of the various D_2O enriching processes so that reactor plant parameters can be established which will permit a low cost and practical reconcentration plant design.

JOHN J. HAPPELL

The Babcock and Wilcox Company
Lynchburg, Virginia
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Crack Formation in Uranium

Internal cracks have been seen in post-irradiation examinations of uranium fuel elements (*1*, *2*). These cracks had random orientation and frequently stopped at grain boundaries. They occurred in fuel elements which had undergone from five to twenty-five reactor shutdowns, had been exposed to over 0.2 atom percent burnup, and had experienced temperatures in the range of 400 to 600°C. Fuel elements undergoing similar exposures and/or maximum temperatures of operation but with different cooling conditions showed no internal cracks on examination.

FAILURE MECHANISM

The coefficients of linear thermal expansion for uranium single crystals vary from 49×10^{-6} to -20×10^{-6} per°C in the [100] and [010] directions at 500°C (*3*). When a polycrystalline piece of uranium undergoes temperature changes, the anisotropic thermal expansions of the various uranium crystals cause large localized strain incompatibilities. These localized or microscopic strain incompatibilities are larger than those caused by the thermal gradients within the fuel material.

During neutron irradiation, uranium behaves in a viscous manner (*4*) and can undergo large deformations. If the

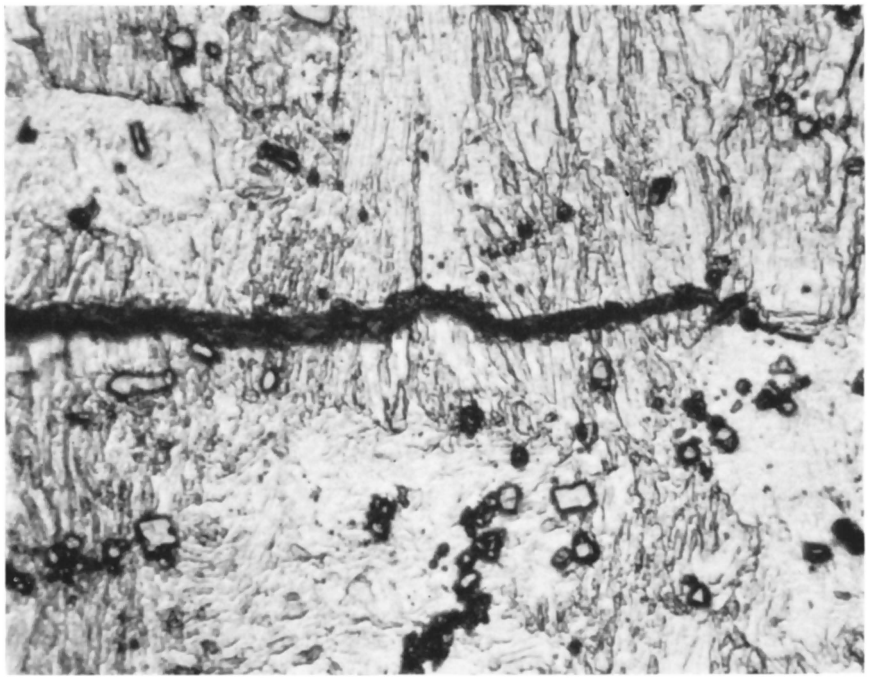

FIG. 1. Photomicrograph of irradiated disks after ten quenchings. Cathode etch at 500× (bright field)

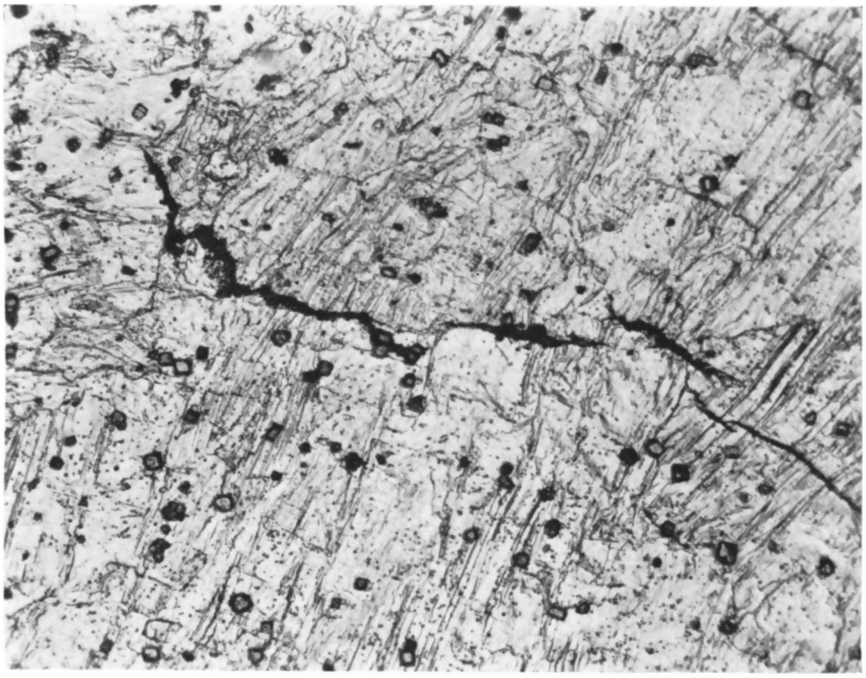

FIG. 2. Photomicrograph of cluster fuel element irradiation to 2200 MWD/T. Maximum temperature ~ 520 (*1*). Cathode etch at 250× (bright field).

uranium is rapidly strained after it has been irradiated (*3*), it is not ductile and is prone to failure after a few rapid strain cycles. Hence, it appears likely that fuel elements with uranium cores develop cracks during reactor shutdowns due to the internal strain incompatibilities caused by the anisotropic crystalline thermal expansions.

EXPERIMENTAL PROCEDURE

In order to obtain experimental evidence of crack formation due to anisotropic crystalline thermal contractions during cooling, the following experiment was run: A one-half inch diameter crack-free rod of uranium (*5*) irradiated to ~1100 MWD/T (0.13 atomic percent burnup) was obtained. The maximum temperature within the rod during irradiation was ~500°C. Two one-quarter inch thick disks from the irradiated rod were cut, polished, and examined for cracks. Each disk was heated to 600°C in a salt bath furnace. Each disk was brought between the jaws of a hydraulically operated vise and the jaws of the vise were closed with a 200-lb clamping force. The jaws of the vise were aluminum covered with a 10-mil thick sheet of stainless steel. The contact resistance between aluminum and stainless steel (~1000 Btu/hr-ft^2) and the thickness of the disk were selected to give a cooling rate representative of that obtained in reactor fuel elements. After one heating and quenching cycle, both disks were repolished and examined. Both disks remained free of observable cracks. One of the above disks was given nine additional heating and quenching cycles. This disk was repolished. Photomicrographs showed small cracks over most of the disk's surface. One crack was larger than the others, Fig. 1. All the tests were conducted in the Radiometallurgy Facility at Hanford in a high-level cell.

CONCLUSIONS

Post-irradiation thermal cycling of irradiated uranium can cause internal cracks. These cracks, Fig. (1), are similar in appearance to cracks observed in experimental uranium fuel elements (*1*), Fig. (2). Since the cracks were formed in a disk with a small thermal gradient and were randomly oriented with respect to the geometry of the disk, the strain incompatibilities due to anisotropic crystalline expansions must have caused these internal cracks.

REFERENCES

1. T. T. CLAUDSON, Final report: Irradiation performance of co-extruded enriched uranium fuel rod-PT-1 P-A172-A. HW-60520, 5/26/59, confidential.
2. J. W. WEBER, Personal notebook, HWS-1949, Engineering Test Reactor Irradiation GEH-3-57.
3. A. N. HOLDEN, "Physical Metallurgy of Uranium." Addison-Wesley, Reading, Massachusetts, 1958.
4. A. H. COTTRELL, AND A. C. ROBERTS, Creep of alpha uranium during irradiation with neutrons, *Phil. Mag.* [8] **1**, 711–717 (August, 1956).
5. W. S. KELLY, Examination of irradiated 7-rod cluster fuel elements PT 1P-46-A (R.M.-182). HW-55360 (March, 1958).

K. R. MERCKX

General Electric Company
Hanford Atomic Operation
Richland, Washington

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