cent of the true rate, depending on the delay, details of the exposure, and U^{235} content of the foils.

The spectrum of gamma pulses giving acceptable coincidences is that to be expected from the known decay scheme. It consists primarily of a large peak at about 106 kev and successively smaller ones at 224, 283, and 335 kev. A constant spectrum of smaller amplitude then extends at least to energies of $1\frac{1}{2}$ to 2 Mev, due presumably to chance events.

The necessary equipment need be capable only of resolving times of the order 3 to 5×10^{-8} sec. Such equipment can be quite simple, and is well within the present state of the art. Present transistor techniques (4) offer promise of excellent stability.

Experiments designed to set an upper limit on usable U^{235} concentrations and to optimize detectors and equipment are continuing.

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Re: "An H₂O–D₂O Moderated Reactor"

A letter to the editor of this journal by Bebbington (1) commenting on an article by Klug and myself (2) points out that we were in error concerning the cost of separating D_2O from H_2O. While Bebbington's remarks concerning the price of the separation process are presumably correct, I should like to mention two rather important points which Bebbington neglected to consider in his criticism.

1. The statement of Bebbington "... if this ratio is to be varied quickly and repeatedly ..." implies that to effect a significant saving in control rods, short-term reactivity change must be provided by varying the admixture of H_2O and D_2O. This implication is not correct, as a major portion of the control in a nuclear reactor is tied up with long term reactivity changes, the compensation for which does not require rapid changes of the H_2O to D_2O ratio. Perhaps Klug and I innocently gave rise to this misconception by pointing out the advantage of operating such a reactor near a maximum in the curve of k_∞ vs H_2O to D_2O ratio. There are several good reasons for doing this which do not require rapid changes of the ratio:

(a) If burnable poisons are used to help compensate for long-term reactivity changes, cross section mismatch generally produces a reactivity curve which increases early in operating life and later decreases. By operating near a peak in the H_2O/D_2O curve, and by using burnable poisons, shim control could be largely if not entirely eliminated.

(b) There are large, but fairly slow, reactivity swings in water reactors due to xenon buildup and decay and water density changes in going to and from operating temperature. These could easily be controlled by varying the H_2O/D_2O concentration.

2. A large portion of the expense in D_2O reactors is due to the equipment necessary to prevent contamination with H_2O vapor from the air. This expense could be eliminated in the type of system we propose, as small amounts of D_2O could be added to compensate for the H_2O contamination.

In conclusion, while we appreciate Bebbington's pointing out our error in the cost of preparing D_2O, we feel that a D_2O–H_2O reactor still has many advantages over conventional systems and warrants further study.

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* * *

To clarify some of the points discussed by Messrs. Klug and Zweifel in "An H_2O–D_2O Moderated Reactor" and the subsequent Letter to the Editor by W. P. Bebbington, I would like to point out that for reactivity control of a pressurized water reactor one need not install equipment to produce highly enriched D_2O from ordinary water or approach either significantly low, or high D_2O enrichment limits during reactor plant operation. Hence, D_2O reconcentration plant capital and operating costs can be kept low. In addition, by proper selection of D_2O concentration limits and reactor control philosophy, one can also eliminate the need for the large reconcentration facilities inferred by Mr. Bebbington. These conclusions are based upon over three years of preliminary and detail design of pressurized water reactors which use H_2O–D_2O ratio variation as a means of reactivity control, (B & W calls this the Spectral Shift Control Reactor—SSCR).

To illustrate, the SSCR utilizes H_2O–D_2O ratio for lifetime reactivity control. D_2O is initially purchased at a concentration of 99.75% and then diluted with light water to give the required start of life concentration of about 75% D_2O. This initial volume of H_2O–D_2O mixture is then gradually diluted with light water by a slow "feed and bleed" process over a core lifetime. At the end of core life the D_2O concentration is 2%. The core is then unloaded and the primary system is drained and refilled with H_2O–D_2O at 75% D_2O concentration. For this control method, it is necessary to have a D_2O concentration plant only large enough to reconcentrate the H_2O–D_2O mixture that is gradually withdrawn during core life to 75% D_2O.

The above control procedure has the following pertinent characteristics with respect to D_2O reconcentration:

1. The required D_2O reconcentration range is only 2% to 75% in D_2O or 37.5 fold—not the 6650 fold required to produce D_2O from natural water (0.015% to 99.75%). Over the reconcentration range 2% to 75% we have found con-

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.

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Received January 23, 1961

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
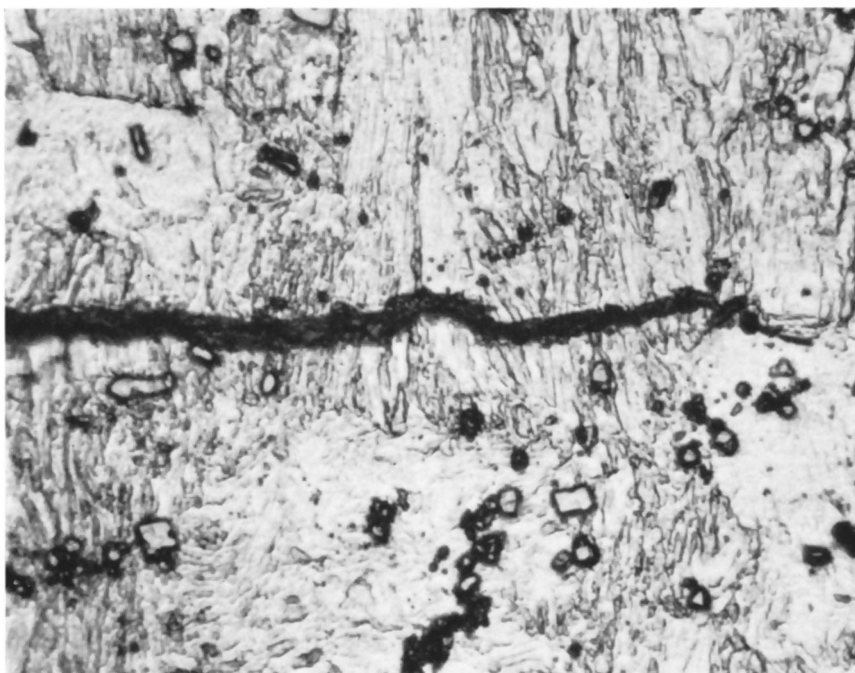

FIG. 1. Photomicrograph of irradiated disks after ten quenchings. Cathode etch at 500X (bright field)