DISCUSSION

N. Ramasubramanian[1] *(written discussion)*—(1) Is there a change in the composition of the second-phase intermetallics associated with the various thermal processings you have used?

(2) Was a difference in the density of nodules observed between the inside and outside surfaces of the tubes? If so, ranking of the tubes based on weight gains could be misleading.

E. R. Bradley et al. (authors' closure)—(1) In this investigation the particle compositions have not been measured.

(2) A detailed investigation of the nodule density on the outside or inside surfaces of the tube samples was not conducted. Cursory visual inspections of the two surfaces suggest similar corrosion behavior, but direct comparisons were not made.

Weight gain measurements include contributions from both uniform and non-uniform corrosion mechanisms. Under the test conditions employed in this investigation, high weight gains are generally related to non-uniform corrosion and provide a good indication of the material sensitivity to nodular corrosion.

K. B. Moorthy[2] *(written discussion)*—(1) Did all materials undergo the same beta-quenching treatment at the billet stage? If so, under what conditions?

(2) What are the nitrogen values in your samples?

E. R. Bradley et al. (authors' closure)—(1) Both TREX were taken from our production stream, and the billets were of the same nominal size and quenched into water from the same beta anneal temperature.

(2) The nitrogen concentration for both materials was very near 25 ppm.

C. E. Coleman[3] *(written discussion)*—Your paper shows that corrosion resistance increases as tin concentration decreases. This suggests that there is a minimum value of tin concentration to provide maximum corrosion resistance. What is this concentration and what are its practical consequences?

E. R. Bradley et al. (authors' closure)—We have not established a minimum tin concentration for nodular corrosion resistance.

R. Graham[4] *(comment)*—Re C. E. Coleman's question: For uniform corrosion we have seen improvements in corrosion rates with Sn concentrations as low as 0.5%.

J. F. Wadier[5] *(written discussion)*—You presented measurements of mean size second-phase particles from SEM and TEM. The two sets of values are significantly different and

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so are the rankings. Can you comment on SEM and TEM accuracy as regards particle size measurement?

E. R. Bradley et al. (authors' closure)—The observed differences in mean particle size can generally be attributed to the measuring technique used. Large particles will not be measured with good statistics by TEM due to the limited field of view and because the larger particles will be lost during preparation of the thin, less than 300 nm, foils. Conversely, the resolution limit of the SEM prevents measurement of the smallest particles and additional smaller particles will be lost during specimen preparation. Therefore TEM measurements are preferred for determining the lower end of the size distribution, while the upper end is best measured by SEM.

The true mean particle size should be somewhere between the mean values from the TEM and SEM distributions. These two distributions can be combined mathematically if sufficient data are available over a common size interval as discussed by Gros and Wadier at the Portland IAEA Technical Committee Meeting on Fundamental Aspects of Corrosion on Zirconium Base Alloys in Water Reactor Environments (IWGFPT/34, 1990).

No attempt was made to combine the two distributions in the present investigation, but the same conclusions would be expected from a more detailed analysis.

L. F. P. Van Swam[6] *(written discussion)*—(1) Did all specimens develop nodules?

(2) If not, should the results be compared on the basis of nodule coverage rather than on the basis of weight gain (which may not be indicative of susceptibility or resistance to nodular corrosion)?

(3) For the weight gain results reported (520°C test), at what weight level do nodules start to form?

E. R. Bradley et al. (authors' closure)—Nodule coverage varied from 0 to 100%. The samples were ranked according to the five level visual standards developed by the ASTM Subcommittee G01.08 task group for conducting a round robin test program to establish the precision of the 773 K, 10.5 MPa steam autoclave test. The major effects of composition and the 1005 K anneal at the final hollow stage were clearly evident from the visual results, but discrimination of the other variables by visual examination was not possible. Weight gain provided a numerical index for evaluating the data and is a useful indicator of a materials susceptibility to nodular corrosion.

Y. S. Kim[7] *(written discussion)*—(1) Could you comment on the mechanism of better corrosion resistance of the tube with high radial texture?

(2) What are the creep properties of the high radial textured tube at 400°C and higher temperatures such as 800°C?

E. R. Bradley et al. (authors' closure)—We are planning additional experiments in this area, but are not prepared to comment on the mechanism at this time. However, the influence of texture on nodular corrosion has been discussed elsewhere.[8]

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[8]Kuwae et al., "Mechanism of Nodular Corrosion," *Journal of Nuclear Materials*, Vol. 119, 1983; Charquet et al., "Heterogeneous Scale Growth During Steam Corrosion of Zircaloy-4 at 500°C," *Zirconium in the Nuclear Industry: Eighth International Symposium, ASTM STP 1023*, American Society for Testing and Materials, Philadelphia, 1989, pp. 374–391.

We did not measure the creep properties of the tubing at either 673 or 1073 K. However, measurements at 655 K show no significant differences between the "low" and "high" radial texture tubing after 250 h.

B. Cheng[9] *(written discussion)*—You showed a beneficial effect of reducing Sn content on the nodular corrosion resistance. Did the low Sn alloy have exactly the same chemistry as the high Sn alloy except for the Sn content?

E. R. Bradley et al. (authors' closure)—Unfortunately, commercial production ingots rarely have "exactly" the same alloy composition for all but one element. The compositions given in Table 1 show tin content to be the major difference in composition with small variations in the other elements. Our experience from autoclave tests of other material lots indicates that the small variations in alloy composition for elements other than tin would not produce the observed differences in corrosion behavior.

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