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FRACTURE MECHANICS EVALUATION
OF REACTOR VESSEL STEELS
QUARTERLY PROGRESS REPORT
FOR THE PERIOD ENDING
MARCH 31, 1967

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Prepared for the New York Operations Office
U. S. Atomic Energy Commission
Under AEC Contract AT(30-1)-3677

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PROGRAM DESCRIPTION

An experimental program will be performed directed towards further development and evaluation of a fracture mechanics approach to the problem of brittle fracture of reactor vessel materials, based upon the use of modified Wedge Opening Loading (WOL) specimens. Experimental testing of a group of reactor vessel steels will be performed to investigate the application of the fracture mechanics technique to these materials in both the unirradiated and irradiated conditions. Because of test reactor dimensional constraints, scaled-up specimens can only be used to obtain pre-irradiation data; therefore, irradiation effects will be determined on small specimens.

Testing in the unirradiated and irradiated conditions will be conducted to determine the variability in fracture toughness of various materials. Materials to be investigated will include base metal, weld and heat affected zone samples from two different heats of a nickel modified, manganese-molybdenum steel and a European forging grade material. Tensile, Charpy V-notch and drop weight specimens from those materials will also be included in the program in order to provide correlation data.

EUFM-100 - Program Management (Summary of Progress)

L. F. Cochran - Project Engineer

This is the third technical progress report on a USAEC-Euratom joint program on fracture mechanics. The previous technical progress reports were

EURAEC-1720 "Fracture Mechanics Evaluation of Reactor Vessel
WCAP-3677-1 Steels Technical Progress Report for the Period
Ending September 30, 1966"

EURAEC-1780 "Fracture Mechanics Evaluation of Reactor Vessel
WCAP-3677-2 Steels Technical Progress Report for the Period
Ending December 31, 1966"

Progress during the period January 1, 1967 through March 31, 1967 is summarized as follows:

- 1) Babcock and Wilcox (B&W) completed construction and testing of the calibration capsule. Temperature uniformity, with and without gas cooling and resistance heating, was unsatisfactory. The design was modified on the basis of experimental results and a second calibration capsule will be built and tested.
- 2) Specimen preparation and pre-irradiation property testing are proceeding as planned.
- 3) The procurement schedule for the 12 in. thick plate is compatible with the overall program. Test reactor limitations make it desirable to test two groups of three capsules each. Material from the 12 in. slab is required October 1, which is compatible with the irradiation schedule for the second test group.

This Task provides for the planning of the irradiation experiment, including the design, manufacture and assembly of the irradiation capsules. Technical direction shall be also provided during the capsule irradiation, capsule disassembly, and post-irradiation examination of specimens. Analysis and evaluation of the experimental results will be performed under this Task.

During this quarter, Babcock and Wilcox (B&W) completed the fabrication of the calibration capsule, analyzed the results of the three dimensional heat transfer calculations, and checked out the calibration capsule in the Babcock and Wilcox Test Reactor (BAWTR). A discussion of the results B&W obtained follows:

Heat Transfer Calculations

The three dimensional calculations indicated that a peak temperature of 265^oF will be achieved with gamma heating of 0.3 watts per gram. One direction heat transfer calculations indicated a peak temperature of 424^oF from gamma heating. The difference appears to be related to gamma heating values used. The one direction heat transfer calculations were hand computed and assumed a constant value of 0.3 watts per gram throughout the capsule. Whereas, the three dimensional computer calculations took into account the attenuation of gamma heating through the thickness of the capsule. The one direction heat transfer calculations were more consistent with the results obtained in the checkout of the prototype capsule than the three dimensional calculations. Whether this is related to greater gamma heating values (greater than 0.3 watts per gram) or to less attenuation than anticipated is not known at this time. The three dimensional calculation indicated

that the temperature at any given depth in the specimen varied by less than 2°F. The total variation through the thickness of the specimen was only 6°F. Thus the temperature distribution through the specimen thickness does not vary appreciably.

Checkout of Calibration Capsule

Irradiation experiments utilizing the calibration capsule were conducted to fully characterize the capsule and BAWTR conditions. The analysis of data obtained from the calibration capsule showed that the temperature variation within the specimens was much greater than calculated and desired. The checkout of the calibration capsule revealed the following:

1. The variation in the temperature within the specimens using only gamma heating varied from 32 to 65°F depending on the location of the capsule along the face of the reflector. The variation in the temperature through the thickness of the specimens was about 10°F. The effect of varying the capsule location on the temperature distribution is shown in Figures 1 through 4. The temperature within the frame of the calibration capsule was as much as 125°F lower than the peak temperature within the specimens.
2. Furthermore, the use of the electrical heaters did not improve the temperature distribution within the specimens as might be expected. This is shown in Figures 5 and 6.
3. The substitution of nitrogen for helium at 4MW operation resulted in a temperature increase of about 220°F. This would amount to a temperature increase of 330°F at a reactor operation of 6MW. The gas pressure within the capsule also had a small effect on the temperature. Increasing the pressure from 0 to 14 psig, resulted in a temperature increase of about 30°F. The variation in temperature was probably the result of the expansion of the outer

Capsule Location: 24' 4-3/16" Below Floor
 Reactor Power: 6.0 MW
 Electrical Heat: None

8 - 1/2 T - 1-13/16" Deep
 9 - 3/4 T - 3" Deep
 10 - 1/4 T - 3" Deep
 11 - 1/2 T - 1/2" Deep
 12 - 1/2 T - 1-13/16" Deep

Figure 1 Temperature Distribution without Electrical Heaters - 24' 4-3/16" Below Floor

Capsule Rotated 180° From Figure 1
 Capsule Location: 24' 4-3/16" Below Floor
 Reactor Power: 5.89 MW
 Electrical Heat: None

8 - 1/2 T - 1-13/16" Deep
 9 - 3/4 T - 3" Deep
 10 - 1/4 T - 3" Deep
 11 - 1/2 T - 1/2" Deep
 12 - 1/2 T - 1-13/16" Deep

Figure 2 Temperature Distribution without Electrical Heaters - 24' 4-3/16" Below Floor
 Capsule Rotated 180° from Figure 1

Capsule Location: 24' 7-3/16" Below Floor
 Reactor Power: 5.96 MW
 Electrical Heat; None

8 - 1/2 T - 1-13/16" Deep
 9 - 3/4 T - 3" Deep
 10 - 1/4 T - 3" Deep
 11 - 1/2 T - 1/2" Deep
 12 - 1/2 T - 1-13/16" Deep

Figure 3 Temperature Distribution without Electrical Heaters - 24' 7-3/16" Below Floor

Capsule Location: 24' 1-3/16" Below Floor
 Reactor Power: 5.70 MW
 Electrical Heat: None

8 - 1/2 T - 1-13/16" Deep
 9 - 3/4 T - 3" Deep
 10 - 1/4 T - 3" Deep
 11 - 1/2 T - 1/2" Deep
 12 - 1/2 T - 1-13/16" Deep

Figure 4 Temperature Distribution without Electrical Heaters - 24' 1-3/16" below Floor

Capsule Location: 24' 4-3/16" Below Floor
 Reactor Power: 6.0 MW
 Electrical Heat: Yes, One CAT, Three Heaters

8 - 1/2 T - 1-13/16" Deep
 9 - 3/4 T - 3" Deep
 10 - 1/4 T - 3" Deep
 11 - 1/2 T - 1/2" Deep
 12 - 1/2 T - 1-13/16" Deep

Figure 5 Temperature Distribution with Electrical Heaters - 24' 4-3/16" Below Floor

Capsule Location: 24' 7-3/16" Below Floor
 Reactor Power: 5.96 MW
 Electrical Heat: Yes, One CAT, Six Heaters

8 - 1/2 T - 1-13/16" Deep
 9 - 3/4 T - 3" Deep
 10 - 1/4 T - 3" Deep
 11 - 1/2 T - 1/2" Deep
 12 - 1/2 T - 1-13/16" Deep

Figure 6 Temperature Distribution with Electrical Heaters - 24' 7-3/16" Below Floor

can, which caused a variation in the gap between the outer can and the aluminum heater plates. The temperature profile for the experiments with nitrogen and helium gas is shown in Figure 7.

Redesign of Calibration Capsule

Discussions were held with BAWTR personnel regarding redesign of the prototype capsule. Agreement was reached on the following modifications for the prototype (calibration) capsule:

1. Inside gap to be decreased from 0.018" to a gap of 0.004". (This will permit outside gap to be increased).
2. Outside gap to be increased from 0.018" to a gap of 0.030 to 0.042". (Gap will depend on ΔT to reach 500°F by gamma heating).
3. 0.004" strips (approximately 0.250" in width) will be placed on inside gap to hold specimens from moving. This will maintain inside gap.
4. Use Kao wool as insulator for the capsules. Kao wool will be wrapped around the perimeter of the frame and also a strip will be placed horizontally to break up the transfer of heat by convection.
5. A frame will be constructed such that the capsule will be held in a fixed position in the reactor, relative to the reflectors. (This was not done for the first prototype.)
6. A frame will be provided such that a filter material may be inserted to scatter the gamma rays if primary test indicate that this is a requirement.

The BAWTR will be down the week of April 30, 1967, and present plans call for the second prototype to be checked out at that time.

Irradiation of Fracture Mechanics Specimens

Present plans call for the capsules containing the fracture mechanics specimens to be inserted into BAWTR in September 1967 and positioned along the

Figure 7 Effect of Gas Content on Capsule Temperature

A. Reactor power increased to 5.5 MW.	H. Power reduced to 4 MW because of excessive temperature with nitrogen gas.
B. Heaters turned off; pure He introduced.	I. Nitrogen introduced.
C. Overshoot because of faulty CAT.	J. Pure He in system.
D. Lag caused by loss of γ heating.	
E. Reactor power dropped to 1 MW - 1:42 p. m.	
F. Temperature stabilized.	
G. Heaters turned on.	

North and West faces of the reactor. B&W is planning to insert three capsules into the test reactor per irradiation cycle. The length of the irradiation cycles is approximately six months. The fast flux ($> 1 \text{ Mev}$) along the face will be about 2.0×10^{12} at the surface of the capsule closest to the reflector. The fast flux along the West face of the BAWTR are shown in Figures 8 through 10. Iron flux wires were used to measure the fast fluxes.

Figure 10
Fast Flux Against West Baffle Plate

EUFM-300 - Pre-Irradiation Testing

T. R. Mager W. S. Hazelton S. E. Yanichko

Under this Task, the material required for the test specimens will be procured and the pre- and post-irradiation specimens will be manufactured. The testing of the pre-irradiation specimens will be carried out and the results developed for analysis and evaluation under Task EUFM-200.

The program for determining the capability of Westinghouse Atomic Power Divisions (WAPD) test equipment was completed. Four (4) 1T and three (3) 2T WOL specimens were tested at various temperatures, and satisfactory results were obtained. Previously 1X WOL specimens were tested using WAPD equipment as part of WAPD's continuous pressure vessel surveillance program. It was concluded that the test equipment is capable of testing 1X, 1T and 2T WOL specimens. A clip gauge was used to measure the crack opening displacement.

Specimen Fabrication

The machine shop (Tooling Specialists, Inc.) that submitted the lowest bid in response to the renewed request for quotations for machining the WOL specimens was evaluated for capability and was qualified as a vendor. WOL specimens were machined from the AEC approved materials, SA508 Class II European forging grade steel and the SA533 Grade B Class I (MnMo with Ni) from the 8" thick plate. Sixteen (16) 1X's and twelve (12) 1T's were machined from each material. These specimens are presently being fatigue cracked. The required 2T WOL specimens are presently being machined.

Tensile and Charpy V-notched impact specimens were machined from both the SA508 Class II and SA533 Grade B Class I materials. The tensile properties of both steels were evaluated from -250°F to +600°F. The results are summarized in Table I and shown in Figures 11 and 12.

TABLE I
Pre-Irradiation Tensile Properties of SA508 Class II and
SA533 Grade B Class I Pressure Vessel Steel

<u>Specimen Identification</u>	<u>Test Temperature °F</u>	<u>0.2% Offset Yield Strength PSI</u>	<u>Ultimate Tensile Strength PSI</u>	<u>Elongation %</u>	<u>Reduction in Area %</u>
SA508-1	-250°F	99,600	112,750	27.6	61.8
SA533A-2	-250°F	94,600	99,675	30.3	67.9
SA508-2	-150°F	83,875	104,850	24.1	63.1
SA533A-1	-150°F	71,650	91,400	28.5	69.1
SA508-3	76°F	77,550	97,525	25.5	65.6
SA533A-3	76°F	62,350	82,125	29.4	69.6
SA508-5	300°F	70,900	89,650	19.1	63.2
SA533B-5	300°F	55,450	73,825	20.6	67.7
SA508-4	600°F	70,800	90,825	20.5	67.4
SA533B-4	600°F	54,650	77,950	25.9	48.5

Figure 11 Pre-Irradiation Tensile Properties of SA533
Grade B Class I Pressure Vessel Steel
(From 8" thick plate)

Figure 12 Pre-Irradiation Tensile Properties of SA508 Class II Pressure Vessel Steel (European Forging Grade)

Metallography

Samples from both the SA508 Class II European forging grade steel and the SA533 Grade B Class I steel from the 8" thick plate were submitted to the Metallography Laboratory. The samples were polished and etched in 2% x nital to reveal the microstructures shown in Figures 13 through 18. Grain size of the steel was determined using the intercept method. Five random hardness measurements were taken per sample. The grain size and hardness values are summarized in Table II.

Procurement of Materials

Because B&W is planning to insert three capsules into the BAWTR per cycle instead of six capsules, additional time becomes available to procure the 12 inch thick plate of SA533 Grade B Class I (MnMo with Ni) steel. The procurement schedule of the 12 inch thick plate is now compatible with B&W's capsule irradiation schedule (Task EUFM-200) and a substitute material is not required.

Figure 13 SA508 Class II - Two Representative Views - After Stress Relief Heat Treatment 1150°F - Top Surface of Plate - 500X

Figure 14 SA508 Class II - Two Representative Views - After Stress Relief Heat Treatment 1150°F - Center of Plate - 500X

Figure 15 SA508 Class II - Two Representative Views - After Stress Relief Heat Treatment 1150°F - Bottom Surface of Plate - 500X

Figure 16 SA533 Grade Class I - After Stress Relief Heat Treatment
1150°F - Top Surface of Plate - 500X

Figure 17 SA533 Grade Class I - After Stress Relief
Heat Treatment 1150°F - Bottom Surface of
Plate - 500x

Figure 18 SA533 Grade Class I - After Stress Relief
Heat Treatment 1150°F - Center of Plate
- 500x

Table II

Grain Size and Hardness Values of SA533 Grade B Class I
and SA508 Class II Pressure Vessel Steel

<u>Material</u>	<u>Location In Plate</u>	<u>Grain Size (mm)</u>	<u>Grain Size (ASTM #)</u>	<u>Hardness (R_B) (AVE)</u>
SA533B	Top Surface	0.0150	9.0	90.9
SA533B	Center	0.0150	9.0	88.7
SA533B	Bottom Surface	0.0150	9.0	91.5
SA508	Top Surface	0.0224	8.0	96.0
SA508	Center	0.0224	8.0	91.6
SA508	Bottom Surface	0.0189	8.5	95.3