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FRACTURE MECHANICS EVALUATION
OF REACTOR VESSEL STEELS
QUARTERLY PROGRESS REPORT
FOR THE PERIOD ENDING
SEPTEMBER 30, 1967

L. F. Cochrun
Project Engineer

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PRELIMINARY REPORT - U. S. EURATOM EXCHANGE

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PROGRAM DESCRIPTION

An experimental program is being 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 is being 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 being investigated include base metal samples from two different heats of a nickel modified, manganese-molybdenum steel and a European forging grade material; and weld and heat affected zone samples from one heat of a nickel modified, manganese-molybdenum steel. Tensile, Charpy V-notch and drop weight specimens from those materials are included in the program in order to provide correlation data.

EUFM-100 - Program Management (Summary of Progress)

L. F. Cochrun - Project Engineer

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

EURAEC-1879 "Fracture Mechanics Evaluation of Reactor Vessel
WCAP-3677-4 Steels Quarterly Progress Report for the Period
Ending June 30, 1967"

EURAEC-1829 "Fracture Mechanics Evaluation of Reactor Vessel
WCAP-3677-3 Steels Technical Progress Report for the Period
Ending March 31, 1967"

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

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

Progress during the period July 1, 1967 through September 30, 1967 is summarized as follows:

1. The first series of irradiation capsules, containing all material except the 12 inch plate material (which is not yet available), is now being irradiated in the Babcock and Wilcox test reactor. Capsule operation is satisfactory.
2. Procurement of the 12 inch plate is proceeding according to schedule and is compatible with requirements for irradiation testing after the present capsules.
3. Further pre-irradiation test data is reported. Further testing was done in an attempt to explain the apparently anomalous transition temperature behavior of the European Forging Grade material.

EUFM-200 - Irradiation and Analysis

T. R. Mager W. S. Hazelton F. Thomas

This task provides for the planning of the irradiation experiment, including the design, manufacture and assembly of the irradiation capsules. Technical direction shall be 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 following work:

1. The first three irradiation capsules were fabricated, assembled, and all heater wires and thermocouples were found to be operational.
2. Completed fabrication of the capsule holder for the Babcock and Wilcox Test Reactor (BAWTR).
3. Assembly and checkout of the recorder and other instrumentation was completed. The irradiation of the first three capsules in the BAWTR was initiated September 5, 1967. The irradiation of these capsules will continue for five cycles of the BAWTR, about six months.

A typical temperature reading is given in Table 200.1. Thermocouples #1 and #14 appear to read low. Thermocouple #14 was reading 545°F but slowly dropped off to 514°F, thus it appears the thermocouple is faulty. At the moment, it is not possible to tell if #1 thermocouple is reading correctly. When the capsule is rotated 180°F one will be able to determine the correct reading. The location of thermocouples for capsule #1 is given in Figure 200.1. Thermocouple positions for capsules 2 and 3 are identical to those in Figure 200.1.

TABLE 200.1

Typical Temperature For Irradiation Capsules

Date: 11 September 1967

BAWTR Power: 6MW

Thermocouple #Capsule #1

1	515°F
2	542°F
3	545°F (Control)
4	532°F
5	545°F
6	532°F

Capsule #2

7	532°F
8	546°F (Control)
9	537°F
10	532°F
11	541°F
12	525°F

Capsule #3

13	545°F (Control)
14	514°F
15	540°F
16	547°F
17	545°F
18	535°F

Thermocouple Number	Location, inches		
	X	Y	Z
1	1.00	-1.5	0.50
2	3.16	-1.5	0.50
3	4.73	-2.5	0.25
4	4.73	-2.5	0.75
5	6.44	-1.5	0.50
6	8.60	-1.5	0.50

Figure-200.1 Location of Thermocouples
In Irradiation Capsules

EUFM-300 - Pre-Irradiation Testing

T. R. Mager W. S. Hazelton F. Thomas

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.

Procurement of Materials

The procurement of the 12 inch thick plate of SA533 Grade B Class I (Mm Mo with Ni) steel is proceeding as scheduled. The material is currently being heat treated at Combustion Engineering. Oak Ridge National Laboratory has indicated that the material will be available in October of this year.

Specimen Fabrication

The machining of the required 2T Wedge Opening Loading (WOL) specimens from the weldment of a 52 inch diameter, 11 inch thick nozzle cutout of SA533 Grade B steel was completed this quarter. The 1X and 1T WOL specimens from the weldment were fatigue cracked prior to testing. Presently the 2T WOL specimens are being fatigue cracked.

Charpy V-notch impact specimens were fabricated from broken drop weight specimens from the European forging grade steel to study the affect of crack orientation on the apparent transition temperature. Charpy V-notch impact specimens are presently being fabricated from broken drop weights of SA533 Grade B material.

Mechanical Testing

The pre-irradiation testing of the tensile, Charpy V-notch and drop weight specimens fabricated from the weldment material (SA533 Grade B) was completed this quarter. The tensile properties which were evaluated from

-250°F to +600°F are summarized in Table 300.1 and Figure 300.1. The Charpy V-notch specimens were tested at various temperatures for both the heat affected zone and weld material. Test data are shown in Tables 300.2 for the weld and 300.3 for the heat affected zone and figures 300.2 (weld) and 300.3 (HAZ). The drop weight data are shown in Table 300.4. Comparative results are shown below:

30 ft. lb. Energy Transition	< -40°F (Weld)
Temperature (Charpy V-notch)	< -40°F (HAZ)
Nil Ductility Temperature	-50°F
(Drop Weight)	

An attempt was made to clarify the difference in temperatures registered by the European Forging Grade steel in 30 ft. lb. energy transition temperature and the nil ductility temperature (as reported in the previous Quarterly Report of June 30, 1967). The results presented at that time showed the 30 ft. lb. energy transition temperature as determined by Charpy V-notch specimens to be -25°F. Nil ductility temperature obtained by drop weight tests was +50°F, however. To explore this differential a number of Charpy V-notch specimens were cut directly from two of the previously tested drop weight specimens. The drop weight specimens used were those designated as DW-NOK-2 (broken at +40°F) and DW-NOK-5 (broken at +50°F) as listed in the above mentioned, previous Quarterly Report. These specimens were cut and notches oriented in two different directions as shown in the sketch of Figure 300.4. Those samples designated by the prefix N each contained a notch oriented in the same direction as the notch in the drop weight sample itself. Those samples with a letter T each had a notch rotated 90° with respect to the N

TABLE 300.1
Pre-Irradiation Tensile Properties of
SA533 B Class I (Weld)

<u>Specimen Number</u>	<u>Test Temp. (°F)</u>	<u>Yield Point* (psi)</u>	<u>Tensile Strength (psi)</u>	<u>Elongation (%)</u>	<u>Reduction of Area (%)</u>
PW5	600	64,150	84,300	22.0	58.0
PW6		64,550	85,550	22.8	59.5
PW3	300	65,400	80,350	22.8	68.2
PW4		67,200	81,050	22.8	70.1
PW1	76	73,650	87,250	26.6	72.1
PW2		74,150	87,900	26.6	71.3
PW8	-150	88,500	97,350	29.2	69.5
PW9		85,550	96,950	30.0	73.3
PW10	-250	96,950	109,550	27.2	65.4
PW11		97,350	107,750	16.4	57.4

*The results given for the test temperature of 600°F are 0.2% offset

Figure 300.1

Pre-Irradiation Tensile Properties of SA533 Grade B
Class I Nozzle Cutout (Weld)

TABLE 300.2
Pre-Irradiation Charpy V-Notch Impact Data for
SA533 Grade B Class I (Weld)

<u>Specimen Number</u>	<u>Test Temp. (°F)</u>	<u>Impact Strength (Ft.-Lbs)</u>	<u>Fracture Appearance (% Shear)</u>	<u>Lateral Expansion (Mils)</u>
PW16	+160	110	100	86
PW17		115	100	86
PW18		120	100	88
PW13	+110	110	100	84
PW14		113	100	88
PW15		114	100	88
PW10	+60	104	85	82
PW11		100	80	80
PW12		106	90	81
PW7	+10	115	100	85
PW8		77	50	62
PW9		100	75	79
PW4	-20	79	50	64
PW5		77	50	62
PW6		83	60	64
PW1	-40	69	40	56
PW2		61	35	49
PW3		54	35	45

TABLE 300.3
Pre-Irradiation Charpy V-Notch Impact Data for
SA533 Grade B Class I (Heat-Affected Zone)

<u>Specimen Number</u>	<u>Test Temp. (°F)</u>	<u>Impact Strength (Ft.-Lbs)</u>	<u>Fracture Appearance (% Shear)</u>	<u>Lateral Expansion (Mils)</u>
PH16	+160	116	100	81
PH17		126	100	85
PH18		118	100	81
PH13	+110	140	100	87
PH14		119	100	79
PH15		117	100	78
PH10	+60	119	100	79
PH11		133	100	82
PH12		126	100	72
PH7	+10	88	60	65
PH8		123	85	83
PH9		110	70	72
PH4	-20	70	60	52
PH5		97	50	69
PH6		133	85	82
PH1	-40	82	40	59
PH2		53	55	40
PH3		50	50	39

Figure 300.2

Pre-Irradiation Charpy V-Notch Impact Data for SA533
Grade B Class I Nozzle Cutout (Weld)

Figure 300.3 Pre-Irradiation Charpy V-Notch Impact Data for SA533 Grade B Class I Nozzle Cutout (Heat Affected Zone)

TABLE 300.4
Drop-Weight Test Data for
SA533 Grade B Class I (Weldment)

Specimen Length	5 in.
Specimen Width	2 in.
Specimen Thickness	5/8 in.
Support Span	4 in.
Stop Height	0.075 in.
Weight of Head	60 lbs.
Drop Height	5 ft.

<u>Specimen Number</u>	<u>Temperature</u>	<u>Result</u>	<u>N.D.T.</u>
A2B1	0°F	Not Broken	
A2B2	-40°F	Not Broken	
A2C3	-80°F	Broken	
A2C4	-60°F	Broken	
A2D5	-50°F	Not Broken	
A2D6	-50°F	Broken	-50°F

Figure 300.4 **Orientation of Pre-Irradiation Charpy V-Notch Specimens Obtained From Drop Weight Samples**

specimens. The results of tests conducted at the two temperatures of -30 and $+50^{\circ}\text{F}$ are listed in Table 300.5. The results indicate that at the NDT of $+50^{\circ}\text{F}$ the Charpy V-notch energy is still considerably above 30 ft. lbs. where either the N or T specimens are considered. Furthermore, there is no significant difference in impact energy for this forging grade steel with respect to notch direction. The anomalous behavior of the material in the Charpy V-notch and drop weight tests must be considered as yet unresolved.

Fracture toughness testing has continued. The requirements of the type of fracture toughness testing employed are unusual in that it is necessary to compare post-test data to specimen pre-test dimensions to determine if the fracture toughness measured (K_Q) is the critical value (K_{IC}) for the material. In other words, validity of the test can be determined only after testing. Two criteria for validity have been proposed:

1. Reference 1 proposes use of the secant off-set method to determine that the majority of strain is due to crack elongation.
2. Reference 2 proposes (specifically for bend specimens, of which WOL specimens are a modification) that both the crack length and specimen thickness exceed $2.5X(\text{Fracture Toughness}/\text{Yield Strength})^2$.

Fracture toughness measured for specimens meeting these criteria is considered to be the critical value (K_{IC}) for the material. If the criteria are not met, the measured fracture toughness (K_Q) is considered to have been biased by specimen size.

The criterion constant (2.5) proposed by Reference 2 was determined empirically using a different material. Applicability to the present materials has not been established - indications are that the constant for the present

TABLE 300.5
Pre-Irradiation Charpy V-Notch Impact Data for
European Forging Grade Steel
(Specimens Obtained From Tested Drop-Weight Samples)

<u>Specimen Number*</u>	<u>Test Temp. (°F)</u>	<u>Impact Strength (Ft.-Lbs)</u>	<u>Fracture Appearance (% Shear)</u>	<u>Lateral Expansion (Mils)</u>
N40-1	-30	54	20	33
2		44	5	32
N40-3	+50	87	40	64
4		62	30	42
N50-1	-30	7	2	2
2		34	5	19
N50-3	+50	56	25	39
4		50	20	25
T40-1	-30	39	5	26
2		45	5	24
T40-3	+50	85	45	58
4		69	35	49
T50-1	-30	27	2	17
2		23	2	12
T50-3	+50	93	50	64
4		65	30	46

*The number immediately following the prefix letter is the temperature at which the drop-weight sample had been previously tested.

materials does not exceed 2.5 and may be substantially lower. Therefore the stress intensity factors presented in Tables 300.6, 300.7, 300.8, and 300.9 should be accepted as (a) valid K_{IC} results for specimens meeting the criteria or (b) tentative K_Q results for specimens not meeting the criteria. Final analysis of the data will not be made until the pre-irradiation testing of a given material is completed.

-
- (1) J. E. Srawley, Notes Pertaining to Sect. 7.3.2 of Draft Recommended Practice, "Interpretation of Test Record and Calculation of K_{IC} ," January 2, 1967.
 - (2) ASTM, E24 Sub I Task Group, "Recommended Practice for Plane-Strain Fracture Toughness Testing of High Strength Metallic Materials Using a Fatigue-Cracked Bend Specimen," draft of proposal practice, December 14, 1966.

TABLE 300.6
Results of WOL Fracture Toughness Tests
SA533 Grade B Class I (From 8" Plate)

Specimen Number	Size	Temp. (°F)	Y.S. (ksi)	a. (in.)	a./W	Plastic Zone Size r(in.)	Stress Intensity Factor (K_{IC}, K_Q) See Text ($ksi\sqrt{in.}$)	Validity (See Note)
8"-5	1-X	-320	110.0	0.617	0.548	0.004	31.6	1
1T4	1-T	-320	110.0	0.939	0.368	0.005	32.5	1
8"-4	1-X	-250	94.6	0.562	0.500	0.008	37.1	1
8"-3	1-X	-250	94.6	0.625	0.556	0.011	44.0	1
1T6	1-T	-250	94.6	0.951	0.372	0.010	40.8	1
1T1	1-T	-250	94.6	1.035	0.406	0.006	31.2	1
8"-1	1-X	-200	82.5	0.539	0.479	0.015	43.2	2
1T11	1-T	-200	82.5	0.944	0.370	0.010	35.6	1
1T8	1-T	-200	82.5	1.042	0.408	0.014	42.8	1
1T10	1-T	-175	78.3	0.916	0.359	0.025	55.5	2
8"-6	1-X	-150	75.3	0.531	0.472	0.041	67.9	2
1T7	1-T	-150	75.3	1.056	0.414	0.025	51.7	2
1T9	1-T	-150	75.3	1.083	0.424	0.027	53.4	2
3	2-T	-150	75.3	1.830	0.358	0.020	46.9	1
4	2-T	- 50	67.5	1.820	0.355	0.052	69.2	2

Note: 1 Meets both criteria; a. and B greater than $2.5 (K_{IC}/y.s.)^2$ and secant offset
2 Fails a. and B greater than $2.5 (K_{IC}/y.s.)^2$, meets secant offset

TABLE 300.7
Results of WOL Fracture Toughness Tests
European Forging Grade Steel

Specimen Number	Size	Temp. (°F)	Y.S. (ksi)	a. (in.)	a./W	Plastic Zone Size r(in.)	Stress Intensity Factor (K_{IC}, K_Q) See Text ($\text{ksi}\sqrt{\text{in.}}$)	Validity (See Note)
17	1-X	-320	115.0	0.589	0.524	0.006	39.6	1
24	1-X	-320	115.0	0.468	0.416	0.003	27.5	1
T4	1-T	-320	115.0	0.936	0.367	0.008	47.5	1
19	1-X	-250	99.6	0.616	0.547	0.011	47.9	1
B5	1-T	-250	99.6	0.917	0.360	0.014	51.3	1
T2	1-T	-250	99.6	0.943	0.370	0.015	53.9	3
26	1-X	-200	90.0	0.465	0.413	0.011	41.2	2
B3	1-T	-200	90.0	1.056	0.414	0.028	68.2	2
T6	1-T	-200	90.0	0.905	0.355	0.019	55.0	1
B6	1-T	-200	90.0	0.919	0.364	0.023	60.8	2
T4	2-T	-200	90.0	1.831	0.359	0.012	43.3	1
T1	1-T	-150	83.9	0.939	0.368	0.025	57.7	2
B2	1-T	-150	83.9	0.936	0.367	0.039	73.2	4
T3	1-T	-150	83.9	1.048	0.412	0.059	97.8	4
T6	2-T	-100	79.5	1.835	0.339	0.026	56.0	1
B3	2-T	-100	79.5	1.819	0.357	0.053	79.2	4
T1	2-T	0	74.0	1.998	0.390	0.078	92.7	4

Note: 1 Meets both criteria; a. and B greater than $2.5 (K_{IC}/y.s.)^2$ and secant offset
 2 Fails a. and B greater than $2.5 (K_{IC}/y.s.)^2$, meets secant offset
 3 Meets a. and B greater than $2.5 (K_{IC}/y.s.)^2$, fails secant offset
 4 Fails both criteria

TABLE 300.8
Results of WOL Fracture Toughness Tests
SA533 Grade B Class I (Weld)

Specimen Number	Size	Temp. (°F)	Y.S. (ksi)	a. (in.)	a./W	Plastic Zone Size r (in.)	Stress Intensity Factor (K_{IC}, K_Q) See Text ($ksi\sqrt{in.}$)	Validity (See Note)
PW4	1-X	-320	115.0	0.518	0.460	0.004	29.7	1
PW5	1-X	-320	115.0	0.505	0.451	0.003	27.2	1
PW6	1-X	-250	97.0	0.475	0.424	0.008	37.6	1
PW13	1-X	-250	97.0	0.503	0.447	0.007	37.8	1
PW2	1-X	-250	97.0	0.519	0.463	0.020	65.7	2
PW7	1-T	-250	97.0	0.958	0.376	0.010	43.6	1
PW6	1-T	-250	97.0	0.935	0.367	0.025	67.7	2
PW13	1-X	-225	93.5	0.506	0.452	0.021	62.3	2
PW16	1-X	-225	93.5	0.500	0.446	0.014	57.7	2
PW3	1-X	-225	93.5	0.485	0.433	0.013	47.8	2
PW3	1-T	-225	93.5	0.921	0.361	0.016	52.8	1
PW4	1-T	-200	90.5	0.959	0.376	0.037	76.0	2
PW8	1-T	-200	90.5	0.933	0.366	0.027	64.3	2

Note: 1 Meets both criteria; a. and B greater than $2.5 (K_{IC}/y.s.)^2$ and secant offset
 2 Fails a. and B greater than $2.5 (K_{IC}/y.s.)^2$, meets secant offset

TABLE 300.9
Results of WOL Fracture Toughness Tests
SA533 Grade B Class I (Heat Affected Zone)

<u>Specimen Number</u>	<u>Size</u>	<u>Temp. (°F)</u>	<u>Y.S. (ksi)</u>	<u>a (in.)</u>	<u>a/W</u>	<u>Plastic Zone Size r (in.)</u>	<u>Stress Intensity Factor (K_{IC}, K_Q) See Text ($ksi\sqrt{in.}$)</u>	<u>Validity See Note</u>
PH6	1-X	-320	110.0	0.511	0.456	0.004	30.3	1
PH7	1-X	-250	94.6	0.500	0.447	0.009	40.4	1
PH4	1-T	-250	94.6	0.925	0.362	0.011	44.2	1
PH3	1-T	-225	89.0	0.909	0.356	0.034	75.0	2
PH3	1-X	-200	82.5	0.515	0.460	0.021	56.5	2
PH1	1-T	-200	82.5	0.908	0.356	0.057	90.5	2

Note: 1 Meets both criteria; a. and B greater than $2.5 (K_{IC}/y.s.)^2$ and secant offset
2 Fails a. and B greater than $2.5 (K_{IC}/y.s.)^2$, meets secant offset