Tentative Conclusions

Summary of Conclusions

The following statements summarize the principal conclusions that may be drawn from the tests to date. Upon completion of the entire investigation, it is expected that some of the statements may require slight modification and that considerable amplification of the information will be possible.

1. For medium carbon steels of the semi-killed type, produced under the current specifications for hull-quality plate, the temperatures at which the mode of failure of sharply notched plates changes from a ductile, shear-type to a brittle, cleavage-type may vary from below freezing to well above room temperature (65°F to 70°F).

2. Steels of presumably identical chemical composition may have widely different transition ranges, as determined by flat plate test.

3. There was little difference in behavior between steel B as-rolled and steel B normalized. The metallurgical structures of plates for the two conditions were substantially the same.

4. The indications are that the steels can be arranged in approximately the same order by the Charpy impact test as by the tension tests of wide plates, although the transition temperatures were considerably different for the two types of tests.

5. Both shear and cleavage failures in the flat, notch plates begin with the formation of small cracks at the base of the notch midway between the faces of the plate. It appears that both the shear and the tensile stresses are a maximum in this region rather than at the faces or surfaces of the plate. (Note: This was discussed in some detail in a previous report--Cleavage Fracture of Ship Plate as Influenced by Design and and Metallurgical Factors NS336: Part II--Flat Plate Tests OSRD No. 6452 Serial M-608 January 1946.)

6. Microhardness surveys made on samples cut from fractured plates indicate that even the most brittle specimens may undergo large amounts of plastic strain at the base of the notch. Th maximum degree of strain approaches that found adjacent to the fracture in the necked section of a standard tensile test bar. Away from the notch, the amount of plastic strain in the plate may be very small and in some cases may approach zero.

7. Under some conditions, cracks progress from the base of the notch toward the edges of the plate during loading and may lengthen several inches before maximum load is reached. The presence of these cracks rather than the original notch geometry may govern the final failure of the plate.

8. With the same sharpness of notch and a fixed notch-to-width ratio, the nominal strength of plates of constant thickness decreases with increasing plate width. This is true whether the failures are of the shear or cleavage type.

9. The maximum loads are slightly lower for specimens failing by cleavage than are the corresponding loads for similar specimens failing by shear.

Organization

The investigations were conducted by the University of California in the Engineering Materials Laboratory. M. P. O'Brien, Dean of the College of Engineering was Technical Representative for the Project, NRC-92. The work was under the general direction of Raymond E. Davis, Director of the Engineering Materials Laboratory. G. E. Troxell, Professor of Civil Engineering, Harmer E. Davis, Associate Professor of Civil Engineering, and Earl R. Parker, Associate Professor of Physical Metallurgy, were in charge of technical phases of the investigation. In direct charge of the testing and the general supervision of the work was A. Boodberg. The laboratory work was under direct supervision of F. Brezee and the computing and drafting work was under direct supervision of Joseph D. DeVito. Special studies were conducted by Charles H. Avery and Joseph D. DeVito. The shop work and welding was under the supervision of Elvin L. Whittier. Other members of the project staff who have served either full or part-time included: P. R. Angell, Mary E. Bennett, E. Berliner, D. Berner, E. Betts, E. M. Cleave, T. Dunlop, C. Glassgow, David E. Gibbs, Eloise Hornstein, R. Johnsen, Inez Keklak, Ruth Kimball, G.R. LaForge, S. Lever, J. Logan, E. McLaughlin, J. Mednick, W. Mullins, Jean Neilson, F. Ormsby, R. Payne, D. Peterson, K. T. Rains, Vera Rideout, A. D. Ring, T. Robinson, R. F. Schord, L. Seaborn, D. Unger, T. Yamamoto, Phebe Zimmerman. Harry E. Kennedy, Research Associate in the College of Engineering, served as consultant on special problems.

TABLE 1. -- DESCRIPTION OF STEELS USED IN LARGE FLAT PLATE TESTS

Note: All steels were tested at temperatures selected so as to define the temperature transition range within reasonable limits.

Code Letter for Steel and Manufacturer	Chemical Analysis		Type of Steel	Use in Test Program
	C,%	Mn,%		
A Carnegie-Illinois	0.25	0.47	Semi-killed As rolled	Large cylinders and 72,48,24,12 and 3-in. notched flat plates
B Bethelehem	0.18	0.72	Semi-killed As rolled	72,48,24,12 and 3-in. notched flat plates
B Bethelehem	0.18	0.72	Semi-killed Normalized	72,48,24,12 and 3-in. notched flat plates
C Carnegie-Illinois	0.25	0.49	Semi-killed As rolled	72,48,24,12 and 3-in. notched flat plates
N Lukens	0.13	0.49	3 1/4% Nickel As rolled	72,12 and 3-in. notched flat plates
H Bethlehem	0.16	0.85	Fully-killed As rolled	72,12, and 3-in. notched flat plates
Q Republic	0.23	1.05	Water quenched and drawn	72,12, and 3-in. notched flat plates

TABLE 2. -- PROPERTIES OF PLATE STEEL -- ABSTRACT OF MILL REPORTS

	Steel A	Steel B		Steel C	Steel N	Steel Q	Steel H
	Carnegie-Illinois	Bethlehem		Carnegie-Illinois	Lukens	Republic	Bethlehem
Chemical Composition							
C	0.23	0.16		0.24	0.13	0.21	0.16
Mn	0.47	0.74		0.49	0.49	1.05	0.75
Si	0.02	0.03		0.043	0.22	0.05	0.17
P	0.011	0.011		0.015	0.018	0.011	0.010
S	0.042	0.030		0.033	0.027	0.030	0.022
Ni	--	--		--	3.34	--	--
Heat Treatment	As rolled	One lot as rolled; one lot normalized at 1650° F.		As rolled	As rolled	Water Quenched and drawn at 1300° F.	As rolled
Physical Tests:		As rolled	Normalized				
Yield point, psi.	37,950	35,800	34,800	39,000	49,800	42,600-50,200*	39,800
Ult. strength, psi.	59,910	59,600	58,900	67,400	77,200-79,400	69,300-75,850*	63,100
Elong., % in 2 in.	33.5	--	--	--	25.5	45-53*	--
Elong., % in 8 in.	--	26.0	32.0	25.5	--	--	27.0
Deoxidation Treatment	1 1/3 lb./ton Si/ton in ladle and 1/2 lb./ton of Al in mold	8 1/2 lb./ton of ferro-manganese, 1 1/8 lb./ton of ferro-silicon and 2 1/2 lb./ton of Al-Si; small amount of Al added in mold		6 lb./ton of 80% ferro-manganese and 2.6 lb./ton of 50% ferro-silicon added in ladle; 1/3 lb./ton of Al in mold	--	--	--

* Maximum and minimum values from tests of 10 different plates.

TABLE 3. -- CHEMICAL ANALYSIS OF SAMPLES FROM INDIVIDUAL PLATES

Plate	Condition and Type	Chemical Analysis C %	Mn %
A-1	As rolled, semi-killed	0.27	0.47
A-2	" "	0.25	0.47
A-3	" "	0.22	0.47
A-4	" "	0.25	0.48
A-5	" "	0.24	0.44
B-1	As rolled, semi-killed	0.17	0.71
B-3	" "	0.18	0.70
B-6	" "	0.17	0.73
B-7	" "	0.17	0.68
B-9	" "	0.17	0.71
B-2	Normalized, semi-killed	0.18	0.73
B-4	" "	0.18	0.73
B-5	" "	0.18	0.71
B-8	" "	0.16	0.71
B-10	" "	0.17	0.71
C-1	As rolled, semi-killed	0.25	0.47
C-2	" "	0.26	0.49
C-3	" "	0.23	0.50
C-5	" "	0.26	0.46
C-6	" "	0.25	0.48
D-1	As rolled, fully-killed	0.17	0.52
N-1	As rolled, nickel alloy*	0.18	0.48
N-2	" "	0.17	0.48
N-3	" "	0.15	0.50

*Nickel content - 3.34 percent

TABLE 4. -- RESULTS OF STANDARD TENSION AND HARDNESS TESTS

(Sheet 1 of 2)

Type of Steel	Plate No.	Type of Bar[a]	Orientation[b]	Tensile Properties				Hardness, Rockwell B Numbers
				Yield Point, psi.	Tensile Strength, psi.	Elong. %[c]	Red. in Area, %	
A	A1	.505	T	34,575	57,875	42.0	57.3	61
		.505	L	35,550	58,800	42.8	60,8	
		Square	L	35,070	58,460	50.5	62.0	
		Flat	L	34,510	58,320	34.0	58.4	
	A2	.505	T	35,890	55,700	43.3	59.7	60
		.505	L	36,200	57,630	44.7	62.4	
		Square	L	34,380	58,190	53.2	64.0	
		Flat	L	32,950	57,860	32.4	61.6	
	A3	.505	T	36,500	58,500	42.0	53.7	60-62
		.505	L	35,500	58,400	43.0	60.7	
		Square	L	36,620	58,630	51.0	63.6	
		Flat	L	35,380	58,620	36.6	64.1	
B As Rolled	B1	.505	T	34,600	56,950	44.3	63.0	60
		.505	L	32,200	57,050	44.8	65.0	
		Square	L	32,460	57,680	48.8	67.2	
		Flat	L	32,210	56,460	35.0	65.5	
	B3	.505	T	31,230	55,640	44.3	57.9	58
		.505	L	32,050	55,850	42.8	67.5	
		Square	L	32,700	56,350	54.8	66.8	
		Flat	L	31,960	57,680	32.8	64.3	
	B6	.505	T	33,500	56,950	42.0	62.2	60
		.505	L	30,350	56,680	45.3	70.1	
		Square	L	32,410	57,200	54.5	67.7	
		Flat	L	31,960	56,880	33.9	64.3	
	B7	.505	T	33,500	56,500	43.0	60.8	61-63
		.505	L	33,050	57,150	45.7	71.5	
		Square	L	--	--	--	--	
		Flat	L	--	--	--	--	

a - .505 = A.S.T.M. std. round 0.505-in. dia. bar; square = full thickness of square cross section; Flat = A.S.T.M. std. full-thickness flat bar.

b - L = axis of bar parallel with direction of rolling.
T = " " " perpendicular to " " "

c - Elongations measured on 2-in. original gage length except on std. flat bars for which gage length was 8 in.

TABLE 4. -- RESULTS OF STANDARD TENSION AND HARDNESS TESTS (continued)

Type of Steel	Plate No.	Type of Bar[a]	Orientation[b]	Tensile Properties				Hardness, Rockwell B Numbers
				Yield Point, psi.	Tensile Strength, psi.	Elong. %[c]	Red. in Area, %	
B Norm.	B2	.505	T	36,370	58,320	41.8	60.4	60
		.505	L	37,100	57,930	46.5	67.2	
		Square	L	34,140	57,440	54.0	65.5	
		Flat	L	35,000	56,880	35.0	63.4	
	B4	.505	T	33,480	56,710	41.8	62.7	59
		.505	L	33,410	57,260	45.5	65.4	
		Square	"	31,080	55,470	54.0	66.0	
		Flat	"	30,900	55,140	35.1	64.9	
	B5	.505	T	37,150	58,530	43.2	60.6	60
		.505	L	35,650	58,700	44.8	66.0	
		Square	L	32,300	56,670	55.0	66.8	
		Flat	L	33,870	56,940	34.8	64.9	
C	C1	.505	T	35,500	61,500	40.0	52.2	66
		.505	L	36,330	61,810	41.5	59.6	
		Square	L	35,330	63,000	49.0	59.5	
		Flat	L	35,300	64,600	31.6	57.4	
	C2	.505	T	36,000	68,130	35.5	50.1	69
		.505	L	37,130	68,500	38.0	57.0	
		Square	L	36,200	66,540	45.5	54.2	
		Flat	L	35,650	66,170	30.0	53.0	
	C3	.505	T	35,650	63,850	38.7	54.5	67-74
		.505	L	34,550	63,850	42.2	60.8	
		Square	L	39,100	65,500	47.7	61.0	
		Flat	L	36,260	64,500	31.7	60.1	
N	N1	.505	T	61,000	76,850	37.8	62.0	83
		.505	L	63,000	77,100	37.5	69.7	
		Square	L	--	--	--	--	
		Flat	L	--	--	--	--	
	N2	.505	T	61,500	77,600	38.2	61.0	83-84
		.505	L	59,000	78,100	38.0	62.1	
		Square	L	--	--	--	--	
		Flat	L	--	--	--	--	