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FABRICATION DATA RELATIVE TO THE A 508, CLASS 2 FORGINGS
FOR THE HSST INTERMEDIATE TEST VESSELS

C. E. Childress
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Sponsoring Program or Organization

HEAVY SECTION STEEL TECHNOLOGY PROGRAM

OAK RIDGE NATIONAL LABORATORY
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Fabrication Data Relative to the ASTM
A-508 Class 2 Forgings for the HSST
Intermediate Test Vessels

The HSST program has negotiated a contract with the Taylor Forge Co. of Paola, Kansas, for six 6-in.-thick Intermediate Test Vessels. The vessels will be fabricated from forged components essentially as shown in Fig. 1, except that one vessel will be provided with a 9-in.-ID nozzle, and among the vessels, certain parameters such as types of welds and weld location will be selectively varied. Further, each vessel will be provided with artificially induced flaws of varying size, configuration, and location. Each vessel will serve as a test specimen for demonstrating the capability to predict safe behavior of thick-wall pressure vessels, containing flaws of known dimensions under frangible, transitional and tough loading regimes. Each particular vessel will serve as a go, no-go determination of critical flaw size for a specific set of test parameters.

Fabrication of the vessel components was sublet to two forging manufacturers; National Forge Co., of Irvine, Penna., and Lenape Forge Co., of Lenape Penna. National Forge made the closure flanges (transition sections), the shell courses and a weld test plate which was used by Taylor Forge for qualifying the appropriate procedures. Lenape Forge made the hemispherical heads and the flat heads. All of the components were made from ASTM A-508 Class 2 materials.

Materials for the hemi heads were obtained from a billet with a 32-in.-square cross section, made from a single heat.

The ladle analysis for the heat is as follows:

Ladle

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Cr</u>	<u>Ni</u>	<u>Mo</u>	<u>V</u>
0.19	0.78	0.008	0.022	0.23	0.39	0.82	0.63	0.03

Most of these elements fall within the mid-range requirements of A-508 Cl 2. The specification places a 0.27-max requirement on carbon, but for this heat the carbon is listed as 0.19 percent.

The next 14 figures depict the major steps used in making the hemi heads. Figure 2 shows a section of billet (originally 32 in. x 14 in. x 45 in.) after preliminary forging which consisted of squaring and rounding. The piece is shown being

removed from the furnace following the first reheat. Figure 3 shows the piece being placed in the die. The next figure, Fig. 4, shows the workmen hand-centering the preliminary-forged bar in the die. Figure 5 was made at the beginning of the initial upset stroke. In this operation the surface oxides are loosened and fall to the bottom of the die. After most of the scale is loosened and falls, the die is raised and the loose scale removed (see Fig. 6). Completion of the initial upset stroke is shown in Fig. 7. By close observation it may be seen that the mass was slightly less than enough to completely fill the die to the upper sidewalls. Lenape advised that the total mass was regulated to provide this condition, since the next operation would force the steel to the sidewalls and facilitate machining of the ID surface.

Figure 8 shows the partially forged hemi head being removed from the die to be returned to the furnace for reheating. In Fig. 9 the piece has been reheated to slightly over 2000°F and is being removed from the furnace for continuation of forging. Figure 10 shows a blunt-ended, tapered die placed over the center of the mold and pressed about 6 in. into the steel. The cavity thus formed serves as a centering point for the die used in the subsequent operation. A second die, with a radius approximately the ID of the hemi head (see Fig. 11) is then pressed into the steel. This operation facilitates machining of the ID and forces the steel to the upper sidewalls. The completed forging is shown in Fig. 12 receiving the identification stamping. The temperature of the heads on completion of each forging operation was 1650°F or greater.

A hemi head is shown in Fig. 13, after the austenitizing heat treatment, equipped with thermal buffer and thermocouple, being conveyed to the quench tank for determination of the cooling rate. The head is shown after quenching was completed, in Fig. 14. A partially machined head is shown in Fig. 15.

The hemi heads were heat treated by (1) normalizing at 1650°F, (2) austenitizing at $1560 \pm 25^\circ\text{F}$ and water quenching, and (3) tempering at 1225°F min and cooling in air. All parts were held at temperature for a minimum of 1 hr/in. of metal thickness.

Six hemi heads were required to complete this order, however, it was not practical to provide each of these with thermocouples during quenching. It was decided that one such head would be instrumented during austenitizing and quenching, and the cooling rate thus obtained would be applied to the test specimens which would receive simulated heat treatments in Lenape's Material Heat Cycle Simulator (Data Trak). The cooling rate obtained during the first quenching effort was somewhat faster than anticipated (based on the cooling rate for a flat head of similar mass that was quenched previously and on cooling

rates for 6-in.-thick HSST plate); therefore, a second head was equipped with two thermocouples to recheck the rate. Location of thermocouples and test material is shown in Fig. 16. The cooling rates obtained for the hemi heads are shown in Fig. 17, Curves A and B. Data Trac cooling rate for test specimens was based on the slower cooling rate of Curve B. (All test specimens received a simulated stress relief at $1125 \pm 25^\circ\text{F}$ for 24 hr.) It should be noted that the test results derived from specimens taken from the locations shown in Fig. 16 were not acceptable. It was concluded that this area probably had not received a sufficient amount of working to produce the desired results. Additional specimens were then removed from near the inside radius of the heads and the mechanical test results from these were acceptable.

Figure 18 shows the instrumentation that was provided during tempering of the heads to determine the temperature variation throughout the parts. Four stainless steel sheathed Chromel-Alumel thermocouples were attached to each head, and, as shown, three were tempered simultaneously. The spread in thermocouple readings during tempering of hemispherical heads 1, 5, and 6 is shown in Fig. 19. The tempering temperature in this case ranged from $1290\text{--}1320^\circ\text{F}$.

Each of the flat heads was forged from material of the same heat. The ladle and check analyses for the heat are as follows:

Ladle:

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>
0.19	0.78	0.008	0.022	0.23	0.82	0.39	0.63	0.03

Check:

0.197	0.75	0.019	0.023	0.22	0.87	0.41	0.59	0.01
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The flat heads were forged from sections of billet measuring 26 in. x 26 in. x 13 1/2 in. Each was cubed, then rounded on an open-die press and upset into a 33 in. OD x 10 1/2 in.-deep die. The upset ratio was 2:1. Figure 20 is a sketch of a rough finished head showing the location of the imbedded thermocouples (for determination of cooling rate) and the test material. The cooling rate determined for the flat heads is shown as Curve C in Fig. 17.

The flat heads were also instrumented during tempering to determine the temperature variation through the parts and throughout the furnace. Figure 21 shows the arrangement of the surface-attached, Chromel-Alumel thermocouples used in monitoring the tempering of the flat heads. The spread in thermocouple readings during tempering of the flat heads is shown in Fig. 22. The maximum temperature recorded during this cycle

was about 1300°F.

Partial results of the mechanical testing performed by Lenape on specimens from the flat and hemispherical heads are as follows:

HEMISPHERICAL HEADS

Lenape ID No.	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Reduction in Area(%)	Elong(%) in 2 in. Gage Length	C _v Values @ +10°F (ft-lb)
3	99.3	79.8	68	23	60-60-51
	96	78.7	68	23	47-51-52
4	95	78.7	67	23	74-49-71
	96	79.7	64	22.5	47-44-49
5	95.5	78	62	22.5	41-46-34
	95.6	78.7	62	22.5	28-31-36
6	96.5	80.5	67	22.5	28-31-31
	95	78	65	22.5	32-25-33

FLAT HEADS

1	90.5	70.9	66	23.5	82-78-65
	90	72	67	23.5	81-85-47
2	89	69.3	47.4	21.5	42-44-40
	92.5	74	62.5	23.5	36-31-37
3	91	71	56	24	38-41-39
	90.5	70.6	64	23.5	51-54-50
4	90	69	63	23.5	45-43-51
	90	70.3	65	23.5	39-35-52
5	90.1	73.3	62	22.5	35-22-38
	87.5	74.8	64.4	21.5	39-37-37
6	91.8	72.8	41.8	19	50-48-52
	89.2	70.4	49.3	20.5	53-54-47

The flat heads were inspected ultrasonically after all machining was completed. The parts were scanned using a Branson model Z-101-A, 1 in.-diam, 2.25 MHz transducer and SAE 40W oil. The transducer was placed over a smooth flat area on the forgings and the back-reflection signal was adjusted to approximately 75% of full screen height. Scanning was performed from the flat side and from the circumference of each head; each scan path was overlapped 50% to assure complete coverage. Lenape's applicable inspection procedure specified as rejectable

any indication "... accompanied by a complete loss of back reflection not associated with or attributable to geometric configuration ..." In any instance, the greatest loss of back reflection observed was about 40%.

The applicable specification stipulated that all components be subjected to magnetic particle inspection on completion of final machining. Taylor Forge Quality Control manager recommended against such inspection, since Lenape uses the contact prod method for magnetic particle inspection. In lieu of magnetic particle inspection, each part was subjected to liquid penetrant inspection and found to be acceptable.

National Forge Co. made the weld test plate, closure flanges, and the shell courses. The test plate and closure flanges were made from ingots poured from single melts. The shell courses were made from two ingots, each of which was poured from two melts. National's heat treatment procedure stipulated that each of the components be (1) normalized at 1640-1750°F, (2) austenitized at 1550-1620°F, (3) quenched in agitated water, and (4) tempered at 1200°F min.

After final forging, the weld test plate was slightly over 8 ft long x 18 in. wide x 6 in. thick. Twelve inches of material from one end of the forging was used for preparation of mechanical test specimens. The ladle and check chemical analyses for this item, heat 1-1075, are:

	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>Cu</u>
Ladle	0.22	0.66	0.011	0.012	0.29	0.82	0.38	0.63	0.10
Check	0.22	0.63	0.011	0.012	0.29	0.80	0.37	0.60	0.11

Specimens for mechanical properties testing were stress relieved at 1125 ± 25°F for 30 hr. Cooling of the test material from the stress relieving temperature was done in accordance with Par N532.3 of the ASME Code for Nuclear Vessels, Section III.

Mechanical properties tests made on specimens from the weld test plate showed the following results:

Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Reduction in Area (%)	Elong(%) in 2 in. Gage Length	C _v Values @ +10°F (ft-lb)
90	72.5	69	25	59.5-62.5-56.5
93	73.5	70	25.2	60-44-59

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National reported that this item was tempered at 1240°F. On completion of tempering, the part was cut into four 18-in.-long sections and shipped to Taylor Forge Co. for qualification of the welding procedures which will be used in fabricating the vessels.

The material for the closure flanges was melted and forged at National's Irvine plant. The reported ladle and check chemical analyses for this heat, 9-8584, are:

	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>Cu</u>
Ladle	0.22	0.69	0.008	0.008	0.27	0.82	0.34	0.63	0.09
Check(1)	0.21	0.70	0.008	0.008	0.27	0.82	0.34	0.62	
Check(2)	0.20	0.69	0.008	0.008	0.26	0.80	0.33	0.62	

The ingot from which the closure flanges was made was essentially a truncated cone and weighed 78,000 lb, including the hot top. The temperature of the ingot on removal from the furnace (preparatory to forging) was about 2400°F; the temperature had dropped to 2200°F by the time forging began. Forging was completed in 40 min, at which time the temperature of the part was determined (by optical pyrometer) to be 1580°F. The completed forging was a solid round bar, 41 1/2 in. in diam x 12 ft long.

Shortly after forging was completed, the part was charged into a furnace and held at 800°F for 4 hr. The temperature was then raised at 100°F/hr until the part reached 1700°F and held at this temperature for 22 hr. It was then removed from the furnace and air cooled to about 300°F. With a furnace preheated to 650°F, the part was recharged and held at this temperature for 3 hr. It was then heated at a rate of 75°F/hr to 1260°F and held for 44 hr, furnace cooled at 50°F/hr to 1100°F then air cooled to ambient temperature. On completion of the post forging heat treatment, the part was subjected to preliminary ultrasonic inspection.

The rough forging was now ready for trepanning, final heat treatment and cutting. The ingot was first rough-turned to 39 1/2 in. OD, and a 14 1/2 in. diam section was trepanned from the center essentially as shown in Fig. 23. In this form, the forging was subjected to final heat treatment prior to sectioning.

To determine the temperature profile throughout the length of the forging during heat treatment and the cooling rate during quenching, the part was equipped with 9 Chromel-Alumel thermocouples also shown in Fig. 23. Six of these were surface-attached and 3 were imbedded. The couples were attached prior to normalizing, since the heat treatment cycle would continue uninterrupted.

The spread in thermocouple readings during the austenitizing heat treatment is shown in Fig. 24. It will be noted that the part was held in the austenitizing range for 1 hr/in. of metal thickness. Each of the heat treatments applied to this item (and all of the parts heat treated at National) were performed in vertical furnaces. Quenching was also performed with the parts in the vertical position. Following the 10-hr hold period, the part was secured by the lifting lug (see Fig. 23) from an overhead crane, removed from the furnace and quenched. About 50 sec were required from the time the furnace top was removed and the part completely immersed.

The inlet water piping to the quench tank was arranged to provide agitation of the quench medium. Additionally, a 4-in. IPS water line was installed along the floor of the tank so that the discharge was directed up through the bore of the forging. Throughout the 88-min quench period, the part was alternately raised and lowered to facilitate cooling. The water temperature, at the start of the quench, was 56°F, reached a maximum of 72°F in 25 min, and had returned to 58°F on completion of the quench.

The cooling curves for the three imbedded couples are shown in Fig. 25. (Data for the surface attached couples are not shown since these couples recorded essentially water temperature after 2 min in the quench.) On removal from the water, the surface temperature of the part was found to be about 150°F. The forging was not recharged for tempering until the furnace temperature had dropped below 400°F. This required some 4 hr.

Figure 26 shows the spread in thermocouple readings during the tempering cycle.

Material for mechanical test specimens was secured from the prolongation near the bottom ingot end of the forging (see Fig. 23). The test material was removed after tempering and was subjected to a stress relieving heat treatment of $1125 \pm 25^\circ\text{F}$ for 30 hr. The results obtained from the mechanical tests are:

Ultimate Tensile Strength(ksi)	Yield Strength (ksi)	Reduction in Area (%)	Elong(%) in 2 in. Gage Length	C _v Values at +10°F (ft-lb)
86	64	69	25	52-59-47
87	66			33.5-35-39

Six closure flanges will be made from this forging, and National has assigned them numbers 1 thru 6 beginning at the bottom ingot end (excluding prolongation). Each end has also been identified so that the bottom ingot end of a piece can be distinguished from the top end. These pieces have been shipped

to Taylor Forge in Paola, Kansas, who will be responsible for machining the raw stock into finished parts.

The ingots used to make the shell courses (one ingot provided material for 3 shell sections) weighed about 200,000 pounds. Each was poured simultaneously from two furnace heats at National's Erie plant. The ingot configuration was essentially a truncated cone 76 in. at the top end and 65 in. at the bottom x 12 ft long, excluding the hot top. It will be seen later that the shell courses have been numbered 4 thru 9, although it was originally intended that the numbering sequence would proceed from 1 thru 6. When it became necessary to remake one of the ingots, National decided to drop the originally assigned first three numbers and continue consecutively from 4 thru 9. The ladle and check chemical analyses of the ingot comprising the first three shells (heats 3V-913 and IV-3809), are:

	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>
Ladle	0.26	0.75	0.010	0.014	0.26	0.81	0.45	0.61	0.05
Check	0.27	0.77	0.013	0.015	0.32	0.82	0.43	0.58	0.05
Check	0.27	0.77	0.013	0.013	0.33	0.81	0.44	0.59	0.05

The temperature of the ingot on removal from the soaking pit was 2350°F. During the first forging operation (performed on a 3,000-ton open die press) the ingot was reduced to a 56-in. octagonal cross section, and the length of the forged section was increased by 4 ft. The temperature of the part on completion of the first forging operation was about 1600°F, after which it was returned to the furnace for reheating.

After some 9 hr in the furnace, the temperature of the part had increased to about 2350°F, and it was again removed from the furnace for additional forging. After about 2 hr of forging, the part was reduced to 41 1/2 in. nominal diam with a usable length of 24 1/2 ft, after cropping of the ends.

The post forging heat treatment of the part consisted in the following:

Soon after removing the end-croppings, the usable length was returned to the furnace and "equalized" at 1180°F for 8 hr. On completion of the 8-hr hold, the forging was allowed to furnace cool to 500°F and held at this temperature for 22 hr. Following this 22-hr hold, the temperature was raised at a rate of 90°F/hr to 1180°F and held for 8 hr, then raised at 100°F/hr to 1600°F and held at this temperature for 32 hr. Following the 32-hr hold, the forging was removed from the furnace and air-cooled to 700°F, then returned to the furnace and furnace cooled to 500°F. It was then held at 500°F for 22 hr. After this 22-hr hold, without cooling further, the temperature was raised at 90°F/hr to 1240°F and held for 30 hr. The forging was then

furnace-cooled to below 500°F, thus completing the post-forge heat treatment.

On completion of post-forge heat treatment, the forging received a preliminary ultrasonic inspection, after which it was sawed in to three pieces of equal length (a 15-in. prolongation was left on each end of each piece.)

The parts were then shipped to National's Irvine plant for trepanning, final heat treatment, final machining and inspection. Final heat treatment performed on the shell courses at Irvine essentially consisted of the same procedure applied to the ingot described previously. One shell, National's No.6, was equipped with six surface mounted and three imbedded stainless steel sheathed Chromel-Alumel thermocouples (prior to normalizing) as shown in Fig. 27. The thermocouples were installed to determine the cooling rate during quenching, and to determine the temperature profile throughout the length of the part during heat treatment, especially during tempering.

Curves showing the spread in thermocouple readings during the normalizing and austenitizing heat treatments are shown in Figs. 28 and 29 respectively. On completion of the 6-hr austenitizing heat treatment the part was lifted from the furnace with the handling device shown in Fig. 30. Some 50 sec were required to lift the shell from the furnace and completely immerse it. The quenching details are essentially the same as those described previously for the closure-flange multiple. The temperature of the water immediately prior to quenching was 52°F and 74°F on completion of quenching.

Curves showing the cooling rate data for the three imbedded couples are shown in Fig. 31. Again, cooling curves for the surface mounted couples are not included since they recorded water temperature shortly after immersing. It will be noted that the couple imbedded at 1/4T (from the OD surface) cooled somewhat faster than the pseudosurface couple (located 1/2 in. from the ID surface). It was suspected that the numbering of these two couples somehow became transposed during installation. However, National advised that they rechecked their installation after the tempering operation and confirmed that the arrangement and numbering sequence shown in Figs. 27 and 31 are correct.

The surface temperature of the part, on removal from the water, was about 125°F. The furnace cooled to about 300°F before the shell was recharged for tempering. The spread in thermocouple readings for the tempering cycle is shown in Fig. 32.

Shell courses bearing National numbers 4, 5, and 6 were made from this ingot. Mechanical test material from prolongations from these shells was stress relieved at $1125 \pm 25^{\circ}\text{F}$ for 24 hr. Mechanical test results of specimens from vessels 4, 5, and 6 are as follows:

National ID No.	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Re-duction of Area(%)	Elong(%) in 2 in. Gage Length	C _v Val. at 10°F (ft-lb)	NDTT(°F) P-3 Drop Weight
4	105.5	85	65.4	22	66-55-51	-20
	107.3	87	66.1	22.5	45-54-54	
5	107	86.5	66.3	22.5	44-60-64	-20
	107.5	87	67	22.5	50-53.5-53.5	
6	109.5	88	65.2	22	57-43.5-51.5	-20
	109.5	88	65.9	22.5	39-63-62.5	

The ladle and check chemical analyses for the ingot comprising vessels 7, 8, and 9, heats 3V924 and IV3828, are:

	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>
Ladle	0.27	0.87	0.007	0.012	0.32	0.74	0.34	0.64	0.04
Check	0.24	0.84	0.009	0.011	0.35	0.72	0.35	0.66	0.04
Check	0.25	0.86	0.009	0.012	0.35	0.72	0.34	0.65	0.04

Mechanical test results of specimens from shells 7, 8, and 9 are:

National ID No.	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Re-duction of Area(%)	Elong(%) in 2 in. Gage Length	C _v Val. at 10°F (ft-lb)	NDTT(°F) P-3 Drop Weight
7	106.25	85	65.9	23	57-40-44.5	-20
	103.5	82.5	66.5	22.5	48.5-50-48	
8	103	83	68.6	24	78-71-79	-20
	102.75	82	69	24	85-69-67	
9	107	87.5	67.9	23	62.5-60-55	-20
	107.5	88.5	67.7	23	38.5-72-74	

It will be noted that the tensile properties listed in the above tables are somewhat atypical of A-508 Class 2 materials. In fact, the yield strength values noted above are about equivalent to the expected ultimate tensile strength of the welds which will be used in the vessels. This and other problems presented by the high-strength shells made it necessary to seek some way of lowering the strength properties short of purchasing new shell courses.

Working with material from one of the shells, Berggren and Canonico developed information (shown in following table) which indicated that the strength properties could be lowered to a satisfactory level by retempering.

Summary of Strength and Impact Properties on
Intermediate Vessel Cylindrical Course Material
A-508, Class 2)

Temper Temperature (Hold time: 6 hr)	σ_u	σ_y	C_v			NDT (°F)
			10°F	40°F	150°F	
1280 ^a	106,000 (avg)	85,000 (avg)	55	100		-20
1287				98		
1298				101		
1303	96,250	78,695		100		
1307				98		
1310				95	142	
1311	92,930	73,685		95		
1318				88		
1328				97		
1330	95,840	69,175	75	85		134
1331				80		
1343				48		
1344	96,035	65,250				
1348				47		

^aData obtained by National Forge, verified by ORNL.

The data shown in the previous table appeared to be promising enough to justify retempering one of the shell courses at 1320°F. In considering a temperature of this magnitude (1320°F) they, of course, were concerned about the lower transformation temperature which is thought to lie between 1325-1350°F.

On February 3, 1971, National Forge equipped shell 9 with 7 thermocouples as shown in Fig. 33. One couple was situated at 1/4T from the OD, 5 on the OD surface, and one (No.4) on the ID surface. This shell, too, was tempered in the vertical position, with couple No. 1 to the top of the furnace.

The retempering profile is shown in Fig. 34. It will be noted that the couple on the ID surface (No. 4) lagged behind the others on heat-up. Accordingly, National continued with the heat-up period some 15 hr until it, too, was well within the tempering range before starting the hold period. It will be noted that most of the couples reached about 1320°F during the hold, except No. 4, which never exceeded 1310°F. Considering only the heat-up and hold periods, this figure is quite similar to Fig. 19 which shows the tempering profile for 3 hemi heads.

On completion of the retempering cycle, additional material was removed from the shell prolongation for mechanical testing. Again, the material was stress relieved at 1125°F for 24 hr. The test results for the retempered shell are:

<u>Ultimate Tensile Strength (psi)</u>	<u>Yield Strength (psi)</u>	<u>C_v Values +10°F (ft-lb)</u>
91,500	72,000	66-40-33
92,250	71,500	62.5-79-55.5

Canonico has performed additional metallographic studies on tempered and retempered materials. These studies have shown that there is no apparent difference in the structure of the material which was retempered at 1320°F and the original material tempered at 1270°F.

Fig. 1. HSST Intermediate Test Vessel.

Fig. 2. Preliminary Forged Bar after Removal from Furnace and Prior to Placing in the Die.

Fig. 3. Preliminary Forged Bar Being Centered in Hemispherical Die.

Fig. 4. Hand-Centering of Bar in the Die.

Fig. 5. Beginning of Initial Upset Stroke.

Fig. 6. Raising Die after Initial Upset Stroke to Remove Scale.

Fig. 7. Completion of Initial Upset Stroke.

Fig. 8. Forging Being Removed from Die for Reheating.

Fig. 9. Reheated Forging Being Removed from Furnace.

Fig. 10. Conical Die used to Provide Center Point in Forging.

Fig. 11. Hemispherical Die Being used to form Cavity.

Fig. 12. Applying Identification to Completed Forging.

Fig. 13. Forging Being Conveyed to Quench Tank.

Fig. 14. As - Quenched Forging.

Fig. 15. Beginning of Machining.

Fig. 16. Location of Test Material and Thermocouples in Hemispherical Head.

Fig. 17. Cooling Rates for Flat and Hemispherical Heads.

Fig. 18. Tempering of Hemispherical Heads.

Fig. 19. Spread in Thermocouple Readings During Tempering of Hemispherical Heads 1, 5 and 6

Fig. 20. Location of Thermocouple in Flat Head.

Fig. 21. Tempering of Flat Heads.

ORNL-DWG 71-2694

Fig. 22. Spread in Thermocouple Readings During Tempering of the 6 Flat Heads.

Fig. 23. Location of Thermocouples in the Forging Used to Make the Closure Flanges.

Fig. 24. Spread in Thermocouple Readings During Austenitizing of the Closure Flange Forging.

Fig. 25. Cooling Curves for the Imbedded Thermocouples in the Closure Flange Forging.

Fig. 26. Spread in Thermocouple Readings During Tempering of the Closure Flange Forging.

Fig. 27. Location of Thermocouples on Shell 6.

Fig. 28. Spread in Thermocouple Readings During Normalizing of Shell 6.

Fig. 29. Spread in Thermocouple Readings During Austenitizing of Shell 6.

LIFTED BY OVERHEAD
CRANE FROM THIS END

Fig. 30. Handling Device for Quenching Shells.

Fig. 31. Cooling Curves for the Imbedded Thermocouples in Shell 6.

Fig. 32. Spread in Thermocouple Readings During Tempering of Shell 6.

NOTES:

- 1 THERMOCOUPLE LAYOUT TYPICAL FOR ALL FORGINGS EXCEPT THE ONE FOR VESSEL V-5. (ORNL HAS RECEIVED THE FRACTURE MECHANICS PROLONGATION ON THIS FORGING).
- 2 THE LOCATION OF THERMOCOUPLES SHALL BE MAINTAINED BY MATCH MARKING AND TRANSFER OF IDENTIFICATION THROUGHOUT. ALL MANUFACTURING OPERATIONS SHALL BE DONE.

Fig. 33. Location of Thermocouples on Shell 9 (to be Retempered).

Fig. 34. Spread in Thermocouple Readings During Retempering of Shell 9.