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Metallographic and Hardness Examinations of TMI-2 Lower Pressure Vessel Head Samples

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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Fifteen steel samples were removed from the lower pressure vessel head of the damaged TMI-2 nuclear reactor to assess the thermal threat to the head posed by 15 to 20 metric tons of molten core debris relocating there during the accident. Full sections of thirteen of the samples and partial sections of the other two samples underwent hardness and metallographic examinations at the Idaho National Engineering Laboratory. These examinations have shown that eleven of the fifteen samples did not exceed the ferrite-austenite transformation temperature of 727°C during the accident. The remaining four samples did show evidence of having a much more severe thermal history. The samples from core grid positions F-10 and G-8 are believed to have experienced temperatures of 1,040 to 1,060°C for about 30 minutes. Samples from positions E-8 and E-6 appear to have been subjected to 1,075 to 1,100°C for approximately 30 minutes.

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EXECUTIVE SUMMARY

Fifteen steel samples were removed by metal disintegration machining from the lower head of the TMI-2 reactor pressure vessel for determination of mechanical properties and metallurgical condition following the TMI-2 accident, in which 15 to 20 metric tons of molten core debris relocated onto the lower head. The samples were triangular in shape with the apex penetrating approximately 50 mm into the 141 mm thick lower head. The objective of the investigation was to learn, to the extent possible, the thermal history of the lower head and to determine the post-accident properties of the A533B pressure vessel low alloy steel so that a margin to failure assessment can be performed.

To accomplish this task, an OECD TMI-2 VIP program (Organization for Economic Co-operation and Development Three Mile Island-2 Vessel Investigation Project) was formed by the Nuclear Regulatory Commission (NRC) with the United States and nine European countries and Japan as the participants. Argonne National Laboratory (ANL) was given the responsibility, by NRC, of receiving and decontaminating the triangular-shaped "boat samples," sectioning them into mechanical property and metallurgical specimens, and shipping the finished test specimens to the OECD partners for testing. ANL also provided considerable background information by performing various tests and examinations on the Midland archive material (A533B steel from the lower head of an abandoned reactor that had an almost identical fabrication history).

Full cross sections, including the stainless steel weld cladding, from thirteen of the boat samples were sent to the Idaho National Engineering Laboratory (INEL) for hardness and metallographic examinations for the purpose of mapping the thermal history of the lower head. Only partial sections of the other two samples (low alloy steel only, without the stainless steel weld cladding) were received at INEL and therefore only the A533B steel was examined for these two. (Full cross sections of these two samples, containing the stainless steel cladding, were not able to be decontaminated but hot cell micrographs of the interface area were provided by ANL.) This report gives the results of the examinations performed by INEL on the thirteen full section and two partial section metallographic samples.

Only four of the fifteen samples examined at INEL showed evidence of thermal exposures during the accident exceeding the ferrite-austenite transformation temperature of 727°C. Sample F-10(m-3) is believed to have experienced temperatures of 1,040 to 1,060°C for about 30 minutes, and Sample E-8(m-3) appears to have experienced 1,075 to 1,100°C for 30 minutes. Limited examination of Samples G-8(m-1) and E-6(m-1) at the INEL and micrographs provided by ANL of G-8(408P-3) and E-6(402A-1) showed that G-8 had received a thermal exposure similar to F-10(m-3) and E-6 a thermal exposure similar to E-8(m-3). The evidence for these thermal histories was obtained at locations within the sample very near to the weld cladding/low alloy steel interface. At a depth of 50 mm into the vessel wall, as measured from the inside surface (45 mm from the weld cladding/low alloy steel interface), the temperature was determined to be approximately 100°C lower. The other eleven samples appear to be metallurgically in the as-fabricated condition, which means their peak temperature during the accident was less than the transformation temperature of 727°C, the lowest temperature for which microstructure modifications could be observed.

FOREWORD

The contents of this report were developed as part of the Three Mile Island Unit 2 Vessel Investigation Project. This project is jointly sponsored by eleven countries under the auspices of the Nuclear Energy Agency of the Organization for Economic Cooperation and Development. The twelve sponsoring organizations are:

* The Centre d'Etudes d'Energie Nucléaires of Belgium,
* The Säteilyturvakeskus of Finland,
* The Institute de Protection et de Sûreté Nucléaire of the Commissariat à l'Energie Atomique of France,
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* AEA Technology of the United Kingdom,
* The United States Nuclear Regulatory Commission, and
* The Electric Power Research Institute.

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- developing exchanges of scientific and technical information on nuclear energy, particularly through participation in common services;

- setting up international research and development programmes and undertakings jointly organized and operated by OECD countries.

In these and related tasks, NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Cooperation Agreement, as well as with other international organizations in the nuclear field.

ACKNOWLEDGMENTS

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Metallographic and Hardness Examinations of TMI-2 Lower Pressure Vessel Head Samples

INTRODUCTION

During the TMI-2 accident, 15 to 20 metric tons of molten core debris relocated onto the lower pressure vessel head of the reactor, causing a considerable threat to the integrity of the vessel.[1] The temperature of the molten debris is believed to have been of the order of 2,530°C (2,800 K), and therefore it had the potential of melting or considerably weakening the lower head, which is comprised of 136 mm thick A533B pressure vessel steel clad with 5-mm Type 308L stainless steel. The lower head did not melt or fail in high temperature creep, but contained the debris. This indicates that the steel's temperature was considerably below its melting temperature of 1,515°C, though the temperature may have been well within the regime where failure by short term creep could have occurred. Samples were removed from the lower head for examination of the post-accident condition of the steel. Mechanical properties are to be determined and metallographic examinations performed on the samples. The objective of the investigation reported in this document is to determine by metallurgical methods, to the extent possible, the thermal history, especially the peak temperatures reached, of the lower pressure vessel head during the accident so that an assessment of the margin to failure can be performed. Methods of examination used included, but were not limited to, (1) hardness profiles, (2) general microstructure examinations, and (3) interface reactions between the A533B steel and the stainless steel cladding.

MATERIAL

Slices were taken from each of the "boat samples" that had been removed from the lower head by a metal disintegration machining process. Figure 1 is a schematic showing the relationship of the samples to the lower head. The samples were identified by the core grid position directly above their position on the lower head; the locations and orientations of the samples are shown in Figure 2. From the fifteen boat samples, thirteen full section and two partial section metallography samples were received at the INEL. The metallurgical samples used in this investigation are identified as follows:

Full Section

D-10(m-2)	E-8(m-3)	E-11(m-3)	F-5(m-3)
F-10(m-3)	H-4(m-3)	H-5(m-2)	H-8(m-2)
K-7(m-3)	K-13(m-3)	L-9(m-3)	M-8(m-3)
M-11(m-3)			

Partial Section (low alloy steel only)

E-6(m-1)	G-8(m-1)	H-8(x-series) [longitudinal strips]

The number in parentheses following the boat sample identification designates the section within the boat (see Appendix A for sectioning details). Boat samples E-6 and G-8 had surface cracks in the stainless steel cladding that contained core debris and decontamination of full cross sections of these two samples with the attached cladding was unsuccessful. Therefore, partial sections of the low alloy steel from these samples were examined at INEL, as well as micrographs taken by ANL during hot cell metallography of E-6 and G-8 sections. The H-8(x-series) samples

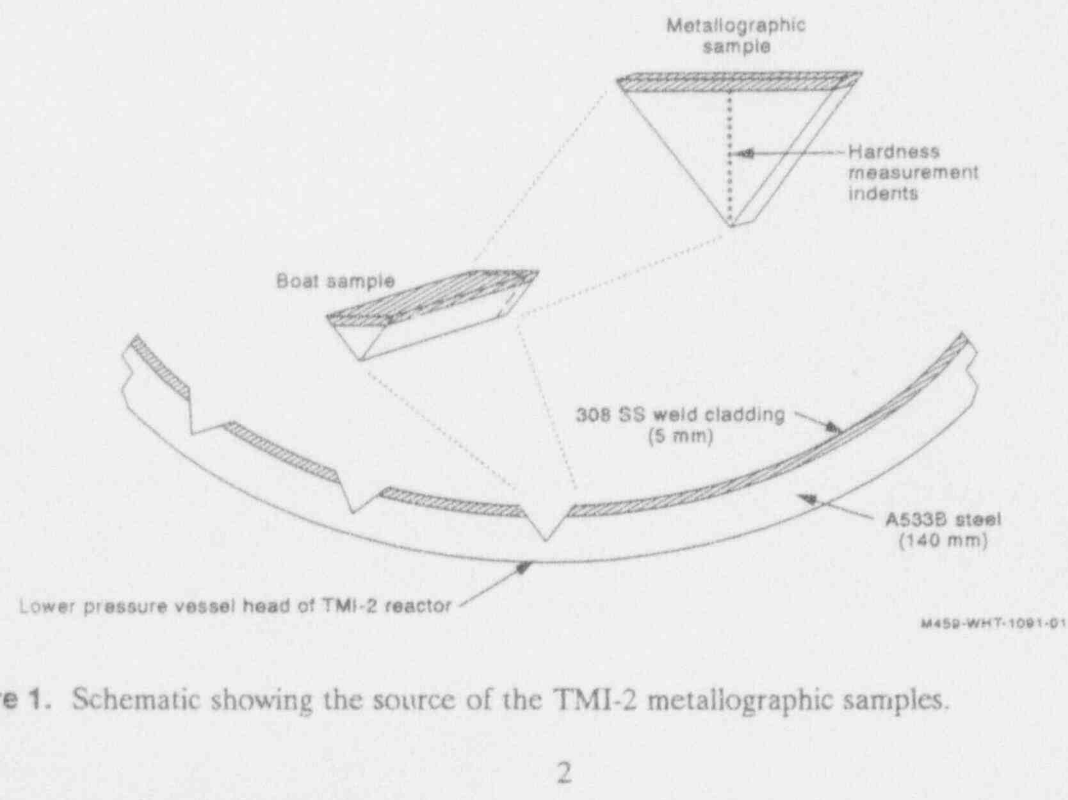

Figure 1. Schematic showing the source of the TMI-2 metallographic samples.

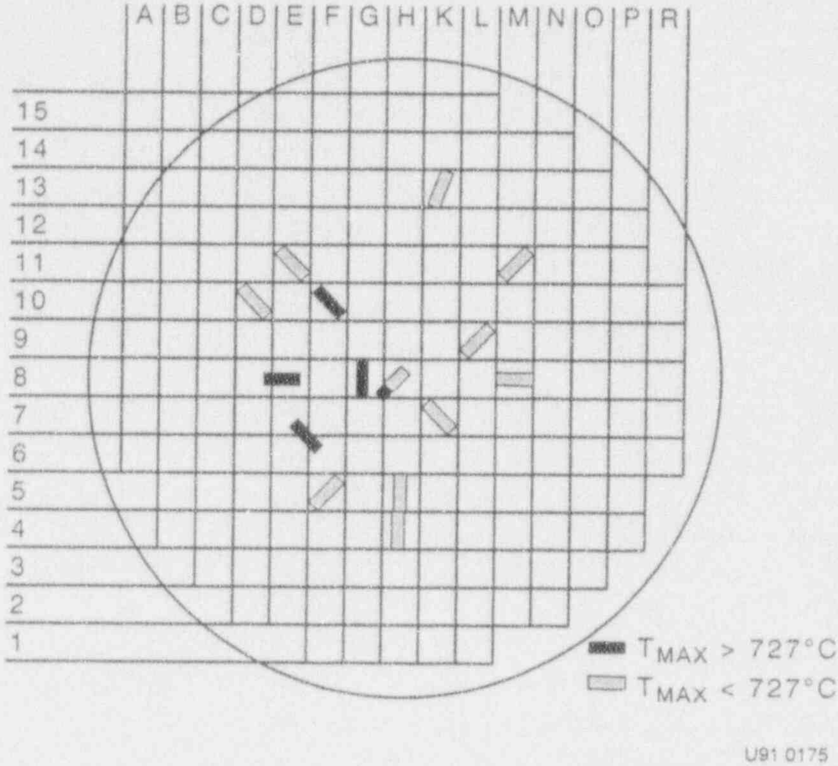

Figure 2. Location of lower head boat samples with respect to core positions.

included longitudinal scrap pieces left over after the H-8 boat sample was sectioned into mechanical property test specimen blanks. These strips were from the end of the boat sample closest to G-8, whereas the H-8(m-2) metallurgical sample was a full cross section taken across the nozzle penetration on the opposite end.

When the samples were received at the INEL, some of them were still slightly radioactive, even though all surfaces had been machined after the slicing. The β-γ activity at contact ranged from <100 (background level) to 9,000 counts/minute. The primary activity was due to Co^{60} and Cs^{137}, but some Sb^{125} was also observed on two samples. This radioactivity was from surface contamination, primarily in the weld clad area, and was removed by a combination of acid etching and abrasive grinding. All samples, except the two mentioned above, were eventually successfully decontaminated to <100 counts/minute so that they could be handled in the "cold" metallurgical laboratory.

SAMPLE EXAMINATIONS

Three different methods of examination were used to assess the thermal history of the samples: (1) hardness, (2) microstructure, and (3) metallurgical reactions at the weld clad interface. Hardness profiles were taken of the samples from the weld cladding to the bottom tip of the triangular piece (see Figure 1). Also, to obtain better resolution without having the hardness indents too close to each other, diagonal traces were taken across part of the weld cladding to a depth of 10 to 12 mm from the interface into the A533B steel. All the hardness measurements were taken using the Rockwell B indenter and then converted to DPH values.

Microstructure was examined using standard metallographic practices. Micrographs were taken at several different magnifications of the area from the weld clad interface to a depth in the A533B steel where the heat effects from the weld cladding operation are no longer seen. The optical metallography and hardness profiles of the thirteen full section TMI-2 samples, the two partial section samples, and the Midland archive material[a] are contained in Appendix A.

The third method of examination involved a closer look at any possible metallurgical reactions at the weld cladding/low alloy steel interface. Optical metallography, microhardness, and limited electron microscopy were all used in this investigation.

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a. The Midland archive material, also A533B steel, was taken from the lower pressure vessel head of the Midland, Michigan reactor built by the same vendor as the TMI-2 reactor and has an almost identical processing history. (See Reference 2 for more details of the Midland archive material and its characterization.)

RESULTS AND DISCUSSION

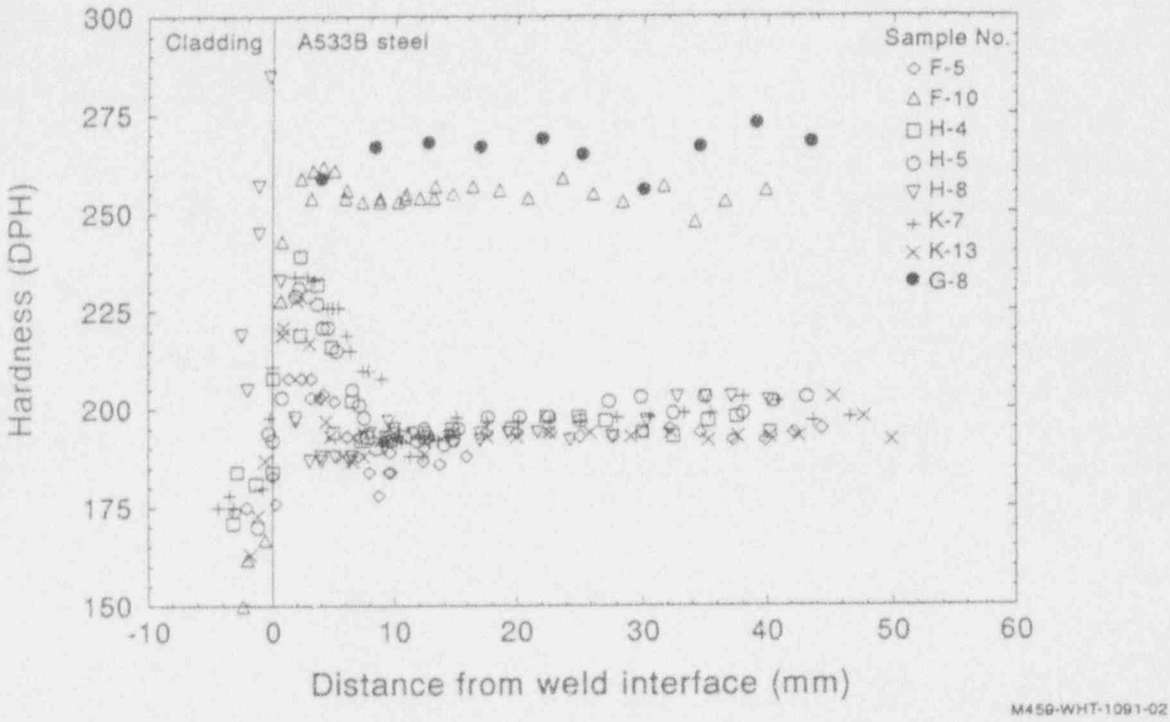
The majority of the samples, including the Midland archive material, exhibited a band 2 to 3 mm below the weld clad interface and 5 to 8 mm wide that could be seen with the naked eye on a polished and etched sample. This band is believed to be due to heat effects from the welding operation. Metallography shows the band to have a very fine-grained structure, and hardness profiles show a marked increase in hardness within the band. Thermal effects from the weld cladding operation would have heated the parent metal to above the ferrite-austenite transformation temperature of 727°C to some depth. The metal would have then been quenched due to the large mass of the lower head plate. This austenitizing and quenching can result in grain refinement and undoubtedly explains the hardening in the band, which could be a Hall-Petch effect from grain refinement, a martensitic transformation, or both. The only full section samples that did not show this band were E-8(m-3) and F-10(m-3), which were shown by hardness measurements to have exceeded the transformation temperature during the accident as will be discussed below.

Hardness Measurements

Figure 3 shows the hardness profiles of all the samples. Samples E-8(m-3) and F-10(m-3) have a markedly different hardness profile than the other samples - the characteristic hardness peak in the band with a subsequent drop to as-fabricated levels has changed to a sharp rise to much higher levels that are sustained throughout the full sample depth. Heat-affected bands from the weld cladding are not evident in these two samples, but have been completely eliminated by the thermal effects of the accident. Although a full depth profile is not available for E-6(m-1) or G-8(m-1), their hardness values are plotted in Figure 3 at the approximate location with respect to the weld clad interface. The hardnesses of these two samples are similar to those of F-10(m-3) and E-8(m-3), indicating that they too had exceeded the transformation temperature.

The hardnesses of the H-8(x-series) strips were measured in a longitudinal direction on the several pieces that were large enough to obtain a good reading. The results of these measurements are shown in Figure 4. A hardness increase is evident as the end closest to G-8 is approached. This observation indicates that the ferrite/austenite transformation temperature was reached on the end of H-8 nearest to G-8.

The final hardness of the TMI-2 samples is a strong indicator that the A533B steel transformation temperature of 727°C (1,000 K) was exceeded during the accident, and the discussion to follow shows that the cooling rate back through the phase change was ≥10°C/minute. Figure 5 compares the final hardnesses of Samples E-8(m-3), F-10(m-3), G-8(m-1), and E-6(m-1) with the results of the cooling rate studies of the Midland archive material. Assuming the Midland material is representative of the TMI-2 lower head material, this figure shows that if the cooling rate had been in the vicinity of 1°C/minute or less, then the final hardness would have been approximately the same as that of the as-fabricated parent metal. Therefore, hardness measurements would not have been very helpful in determining the thermal history due to the accident - they would only reveal that the hardness peak from the heat-affected band from the weld cladding was eliminated. However, the final hardness values for E-8(m-3), F-10(m-3), G-8(m-1), and E-6(m-1) are consistent with cooling rates of ≥10°C/minute and any peak temperature



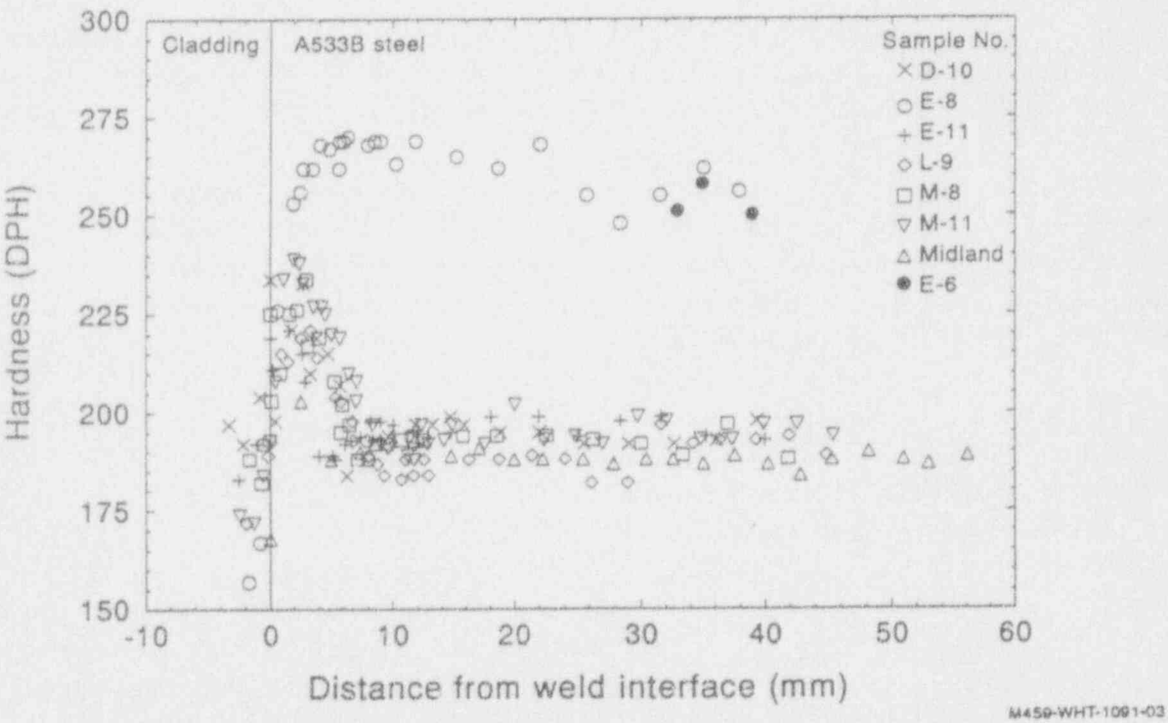


Figure 3. Composite hardness profiles of lower pressure vessel head metallographic samples. Data for eight samples are shown in upper figure; data for remaining seven samples plus Midland archive material are shown in lower figure.

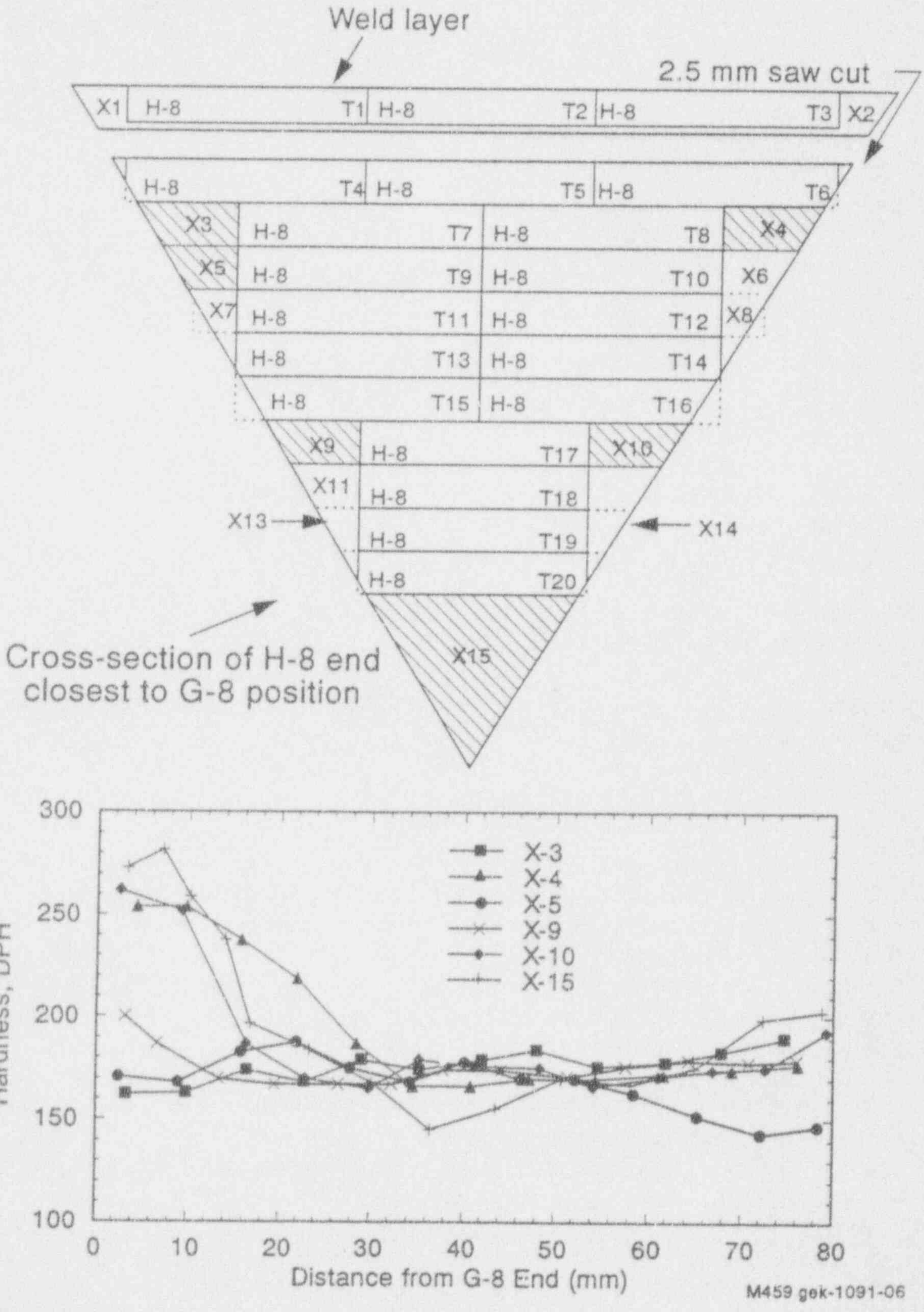


Figure 4. Longitudinal hardness profiles taken from the H-8 (x-series) strips.

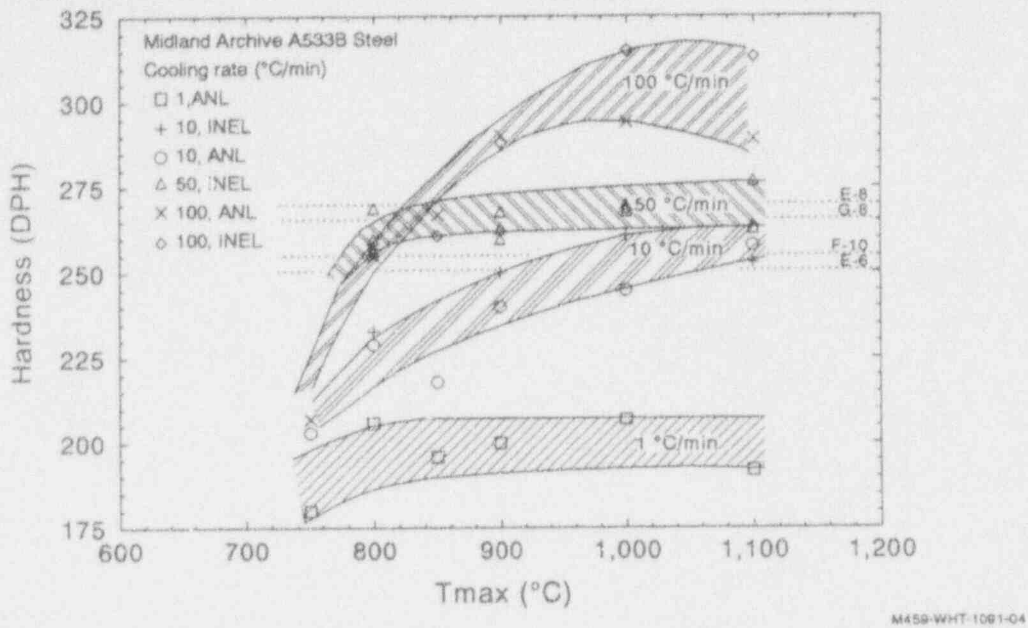


Figure 5. Final hardness of Samples E-8(m-3) and F-10(m-3) compared to cooling rate effects/T_{max} curves for the final hardness of Midland archive material.

from 800 to 1,100°C (1,073 to 1,373 K). Therefore, hardness values of the TMI-2 samples are indicative of two things: (1) whether or not the material had exceeded the transformation temperature, and (2) if it had, some bounds on the cooling rate. However, hardness values are not very conclusive as to the peak temperatures that may have been reached. Other methods were explored to assess peak temperatures.

Microstructure

Other indicators that assisted in determining the thermal history of the lower head during the accident include the general microstructure, which would show evidence of grain growth while in the austenitic phase, and heat-induced metallurgical reactions that may have occurred in the stainless steel or at the A533B steel/weld cladding interface. Even though these indicators are metallurgical phenomena for which time and temperature are interrelated, the determination of boundaries is possible. Also, by using several approaches the probability of converging on the thermal history was much greater.

Carbon diffusion from the pressure vessel steel (0.2% C) into the stainless steel (0.03% C) is evident, and this phenomenon is another possible indicator of thermal history. Figure 6 shows the band of carbon diffusion into the weld cladding for Samples F-10(m-3) and E-8(m-3), known heat-affected samples from the accident. The 0.10 to 0.15 mm band in the stainless steel at the interface has been determined by scanning electron microscopy (SEM) microchemical analysis to be due to carbon diffusion. Figure 7 shows more details of the band of F-10(m-3). Microhardness measurements reveal that the band is very hard (up to 500 DPH) and microcracks, seen in Figures 6a and 7, show that the band is brittle. Although TMI-2 samples believed to not have been affected by the accident exhibited some evidence of carbon diffusion (by microhardness

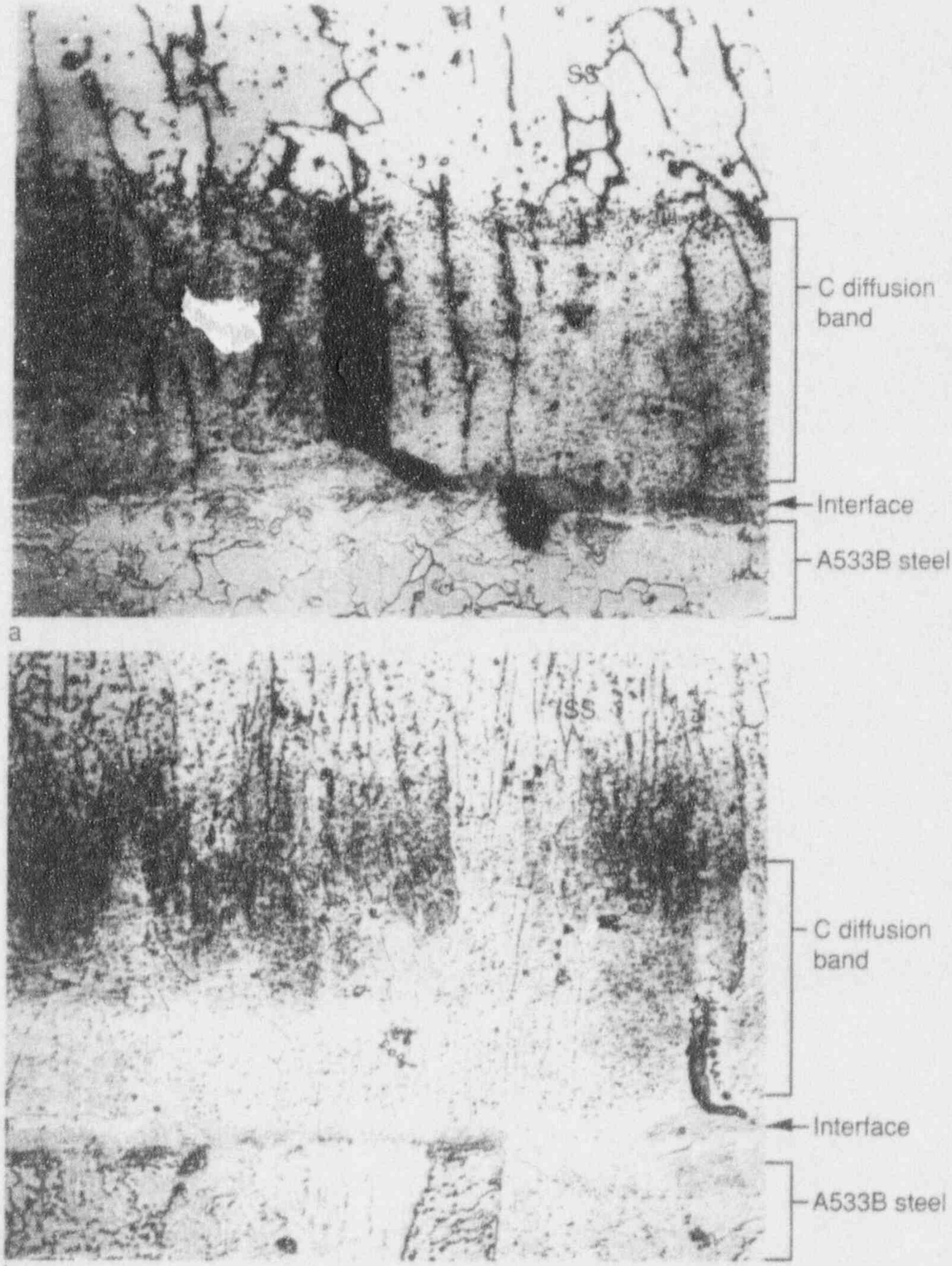


Figure 6. Stainless steel/low alloy steel interface of Samples F-10(m-3) (a) and E-8(m-3) (b) illustrating the band of carbon diffusion into the stainless steel.

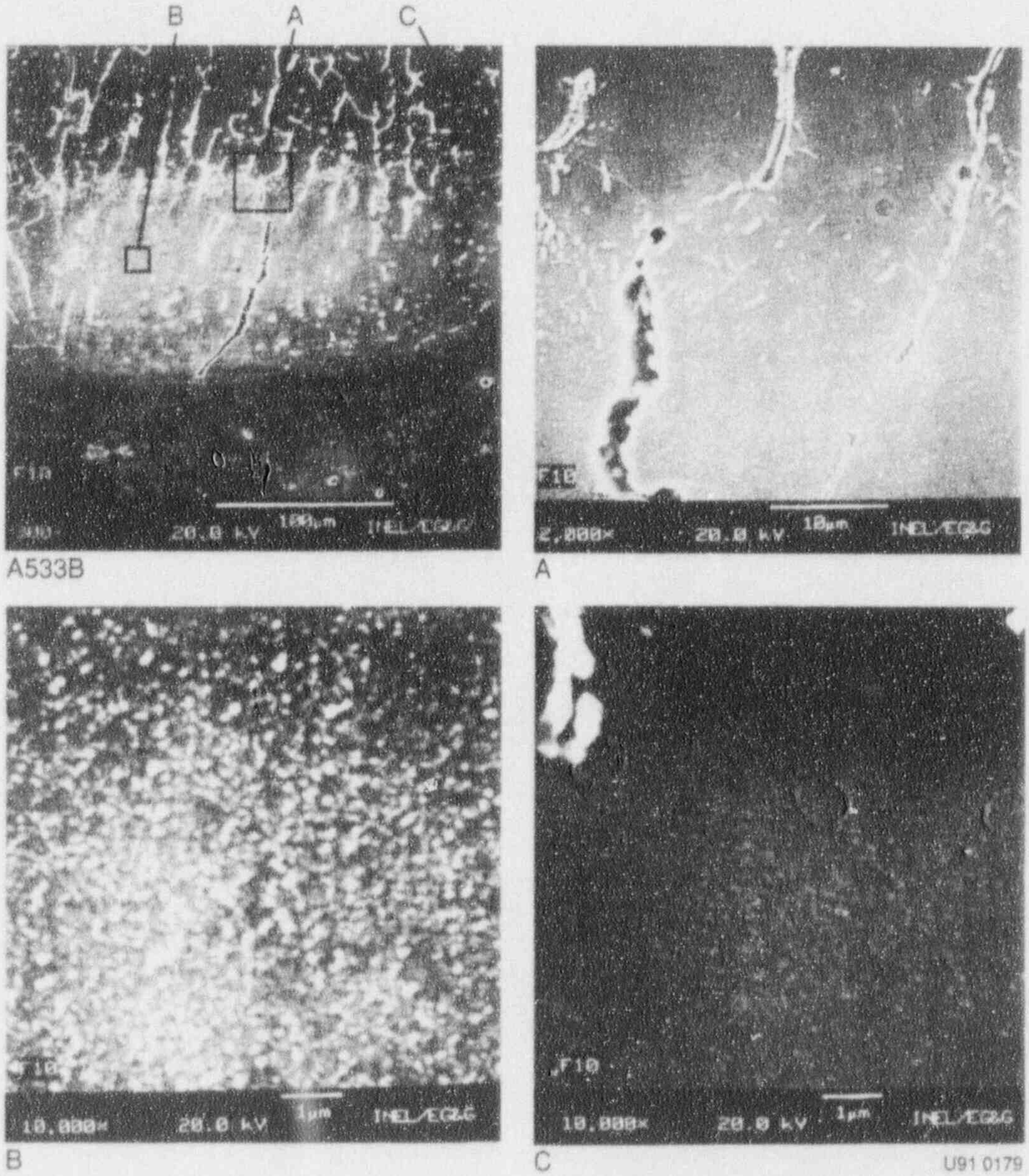


Figure 7. SEM micrographs of the carbon diffusion band [Sample F-10(m-3)].

measurements only, not revealed by metallography) into the stainless steel from the welding operation, it is not so prominent nor as deep as observed in F-10(m-3) and E-8(m-3). Figure 8 illustrates the time/temperature/distance relationship of carbon diffusion into austenite based on theoretical calculations using diffusion coefficients found in the literature.[3] This figure shows that the 0.10 to 0.15 mm diffusion distance observed on Samples F-10(m-3) and E-8(m-3) could have resulted from conditions ranging from 2 minutes at 1,100°C to 90 minutes at 800°C. Thus, the carbon diffusion distance by itself is not conclusive in determining peak temperatures of the lower head, but it is of value in confirming other indications.

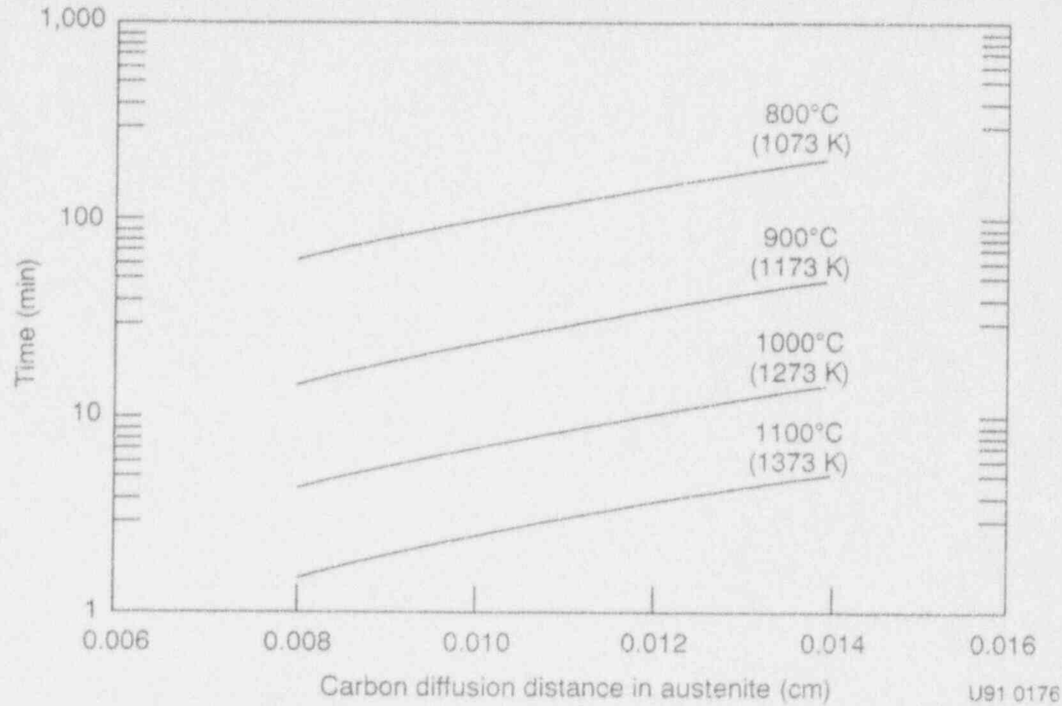


Figure 8. Calculated time/temperature/distance relationship of carbon diffusion into austenite.

Comparison with Standards

To provide a basis for comparison with the TMI-2 samples, Midland archive standards with known thermal histories were prepared. By making the best possible match between the standards and the TMI-2 samples of the combination of hardness, microstructure, carbon diffusion distance, and any interface reactions, an estimate of the TMI-2 sample thermal history was made. The first series of Midland archive standards was prepared by resistively heating flat bars (3 x 25 x 80 mm) in the Gleeble machine to the thermal histories shown in Figure 9. Initially, twelve standards were prepared with T_{max} values of 800, 900, 1,000, and 1,100°C and dwell times of 1, 10, and 100 minutes. The heating rate of 40°C/minute was chosen arbitrarily, but the cooling rate of 50°C/minute was selected because it produced a final hardness similar to that observed in Samples F-10(m-3), E-8(m-3), G-8(m-1), and E-6(m-1). Microstructures from the stainless steel weld cladding, the A533B vessel steel, and the stainless steel/low alloy steel interface from the twelve Midland archive standards are shown in Appendix B. One of the first things that is apparent from this set of standards is a dark feathery line at the interface on the as-received archive sample and all those exposed to temperatures not exceeding 800°C. This line is still partially present on the samples exposed to 900°C for 1 and 10 minutes, but has disappeared (dissolved or dissipated) on all samples exposed for longer times or at higher temperatures. This same dark feathery line, although variable in thickness, is visible at the stainless steel/low alloy steel interface of all TMI-2 samples except F-10(m-3) and E-8(m-3). The stainless steel/low alloy steel interface area was not available for Samples G-8(m-1) and E-6(m-1,) but the ANL micrographs of other sections of G-8 and E-6 that did contain the interface had no evidence of the dark feathery line.

Dwell time at T_{MAX}, min	T_{MAX}, maximum temperature, °C			
	800	900	1000	1100
1	TMIG-15	TMIG-16	TMIG-17	TMIG-18
10	TMIG-19	TMIG-20	TMIG-21	TMIG-22
100	TMIG-23	TMIG-24	TMIG-25	TMIG-26

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All samples
Heat up rate = 40°C/min
Cool down rate = 50°C/min

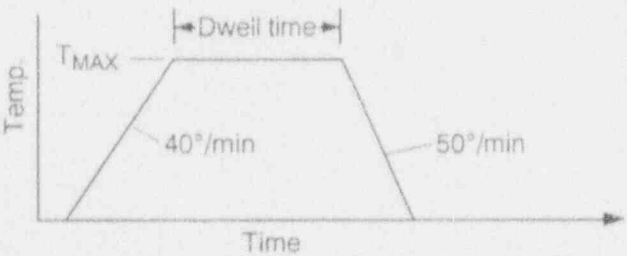

Figure 9. Thermal histories of the 12 Midland archive standards (first series).

It was also noted that in the standards the prior austenitic grain size of the A533B vessel steel some distance away from the interface starts to change quite dramatically after 1,000 and 1,100°C exposures. Directly adjacent to the interface, the low alloy steel grains go through a morphology change. Initially, they have a typical ferritic structure (slightly enlarged due to the weld cladding heat effects). As the temperature increases, the grains are refined with an equiaxed shape and, as the temperature continues to increase, eventually consumed by the growth of the larger austenitic grains.

The morphology of the δ-ferrite islands in the stainless steel weld cladding also changes. At thermal exposures of 1,100°C for 10 minutes and also at 1,000°C for 100 minutes, the δ-ferrite islands begin to lose their slender branch-like interdendritic morphology and become more spherical in shape. It was suspected that this spheroidizing was due to the dissolution of $M_{23}C_6$ carbides, which decorate the austenite-ferrite boundaries at lower temperatures and thus tend to stabilize the shape of the islands. After the carbides dissolve, the δ-ferrite would become more spherical shape to minimize the surface energy. The limited transmission electron microscopy (TEM) examinations performed appear to confirm this speculation. Figure 10 shows the presence of carbides at the austenite-ferrite interface in the stainless steel cladding for Samples K-13(m-3)[b]

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b. Boat Sample K-13 is the sample most likely to be unaffected by the accident since it was not covered by core debris, and therefore should represent the TMI-2 lower head in the as-fabricated condition.

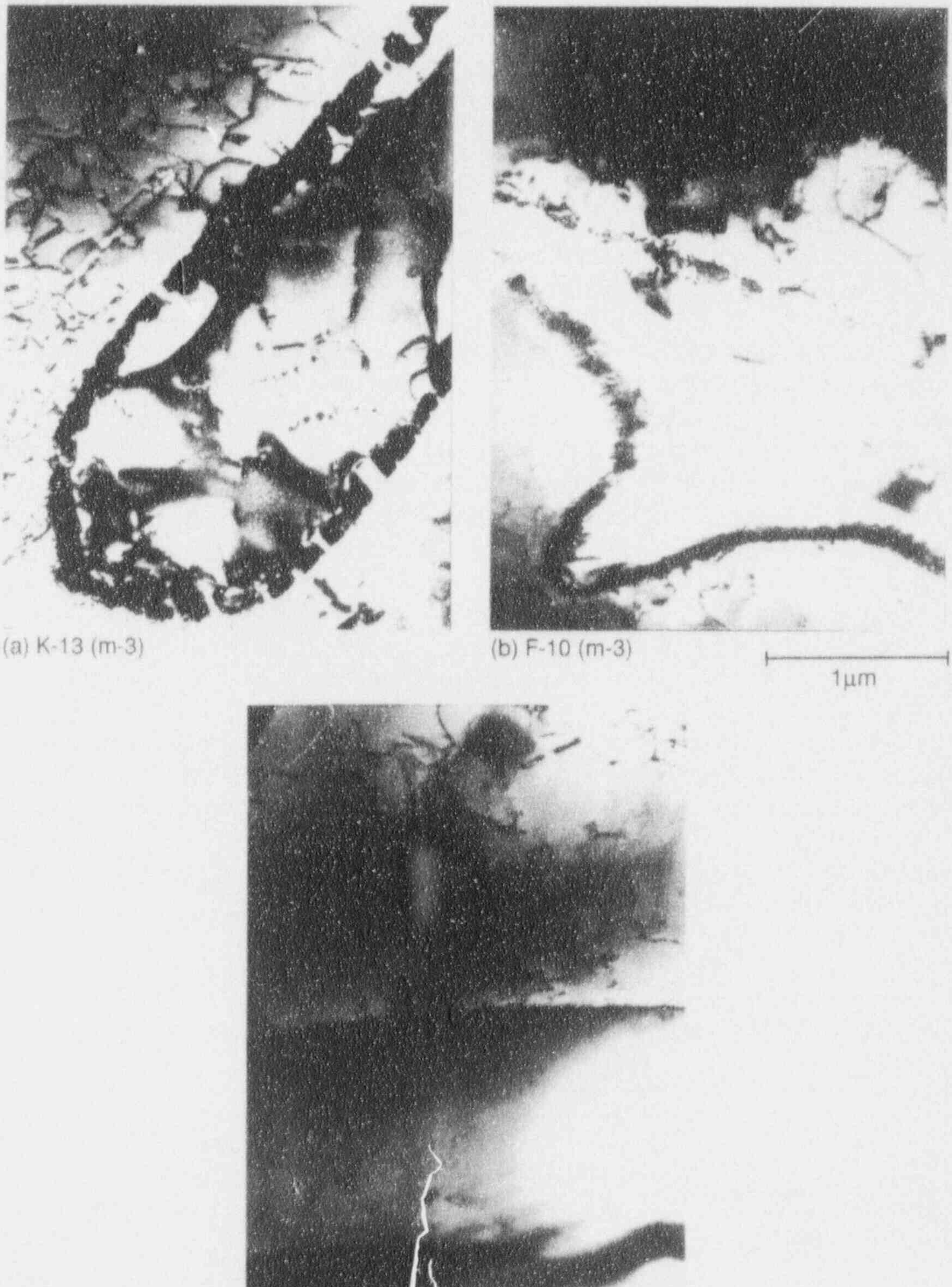


Figure 10. TEM micrographs showing the presence of carbides at the austenite-ferrite interface in the stainless steel weld cladding: (a) Sample K-13, as-fabricated condition, (b) Sample F-10(m-3), carbides starting to dissolve, and (c) Sample E-8(m-3), carbides have dissolved from austenite-ferrite boundary.

and F-10(m-3), but none were observed at an austenite/ferrite boundary for E-8(m-3). The carbides shown in Figure 10 for Sample F-10(m-3) appear to be partially dissolved when compared to those in K-13(m-3). The presence or absence of carbides correlates well with the spheroidizing of the δ-ferrite islands.

Comparing all three areas (stainless steel cladding, interface, and low alloy steel), F-10(m-3) was found to most closely match the Midland archive standard given the 1,000°C exposure for 10 minutes, and the best match for E-8(m-3) falls between the standards exposed at 1,100°C for 10 and 100 minutes.

In an attempt to further refine the time/temperature history of F-10(m-3) and E-8(m-3), additional Midland archive samples were prepared and heat treated at times and temperatures between those of the previous series. For this second series the samples were approximately 3 × 6 × 25 mm in size and were heat treated in a quartz lamp infrared radiant furnace. Using these standards, the best match with sample F-10(m-3) is the archive sample exposed at 1,050°C for 30 minutes and E-8(m-3) falls between the archive samples exposed at 1,100°C for 10 and 30 minutes.

After the time/temperature history of F-10(m-3) and E-8(m-3) had been narrowed down using archive material, 3 x 6 x 25 mm slices were cut from TMI-2 metallurgical Samples H-4(m-3) and M-11(m-3), which are believed to represent the as-fabricated condition. These slices were heat treated as shown in Table 1. These thermal exposures are the same times and temperatures as the second series of Midland archive standards. This action was taken to eliminate, as much as possible, subtle thermal response differences that might exist between the Midland archive material and actual TMI-2 lower head material. Microstructures from the heat-treated slices of H-4(m-3) and M-11(m-3) are shown in Appendix C. Microstructures of F-10(m-3) and E-8(m-3) with the same etch and magnifications and the micrographs from the ANL hot cell sections G-8 (408P-3) and E-6 (402A-1) are also shown in this appendix.

Table 1. Sample identification and heat treatments given the slices from H-4(m-3) and M-11(m-3) samples.

	Maximum temperature (T_{max}, °C)			
Dwell time (T_{max}, (minutes)	950	1,000	1,050	1,100
10	H4-1	H4-2	H4-3	H4-4
30	H4-5	H4-6	M11-1	M11-2
100	M11-3	M11-4	M11-5	M11-6

Heatup rate = °/minute, cooling rate = 50°C/minute

The H-4(m-3) and M-11(m-3) heat treatments showed that the structural changes in the TMI-2 material were very similar to those of the Midland archive material. Some subtle differences in the prior austenite grain size and morphology were noted with the TMI-2 material. Therefore, the heat treated slices from Samples H-4(m-3) and M-11(m-3) were used for the final time/temperature history determinations for F-10(m-3), E-8(m-3), G-8(m-1), and E-6(m-1), even though the final conclusions were the same as those based on the Midland archive material.

In an attempt to illustrate the various metallurgical observations from the prepared standards of Midland archive material and the heat treated TMI-2 material, the diagram shown in Figure 11 was constructed. Since the vessel was stress relieved at 610°C after the weld cladding, no thermal effects from the accident could be detected at or below this temperature and, therefore, the diagram only shows metallurgical observations for temperatures above this point. The lowest temperature indicator, above the stress relief temperature, was the ferrite-austenite transformation, which starts at 727°C and is complete by 810°C. Variations in hardness will be evident when this threshold is exceeded. The next indicator is the dissolution of the dark feathery band at the interface; this occurs between 800 and 925°C, depending on the time. The next indicator of increasing temperature is the appearance of small equiaxed grains in the A533B steel adjacent to the interface that form between 850 and 900°C and disappear between 1,025 and 1,100°C as they are consumed by grain growth in the low alloy steel. The dissolution of the dark feathery band and the formation of the equiaxed grains are believed to be associated with carbon diffusion into the stainless steel cladding. The dark feathery band appears to be some sort of carbide that disperses as the carbon diffuses into the stainless steel. The equiaxed grains, which are not typical for a low alloy steel, appear to be devoid of cementite, undoubtedly due to a loss of carbon into the stainless steel. Grain growth in the A533B steel becomes significant above approximately 950 to 1,075°C, depending on the time involved. The highest temperature indicator shown on the diagram is the spheroidizing of the δ-ferrite islands in the stainless steel cladding, which occurs in the approximate range of 975 to 1,000°C at 100 minutes or 1,100 to 1,125°C at 10 minutes.

The thermal histories were determined by applying the above observations to microstructural examinations of areas near the stainless steel/low alloy steel interface (within 2.5 mm). The temperature gradient through the thickness of the lower vessel head wall was estimated by two methods. First, since the high level of hardness of the four affected samples persisted to the full depth of the boat samples (50 mm from the inside surface, 45 mm from the weld clad interface, see Figure 3), it could be concluded that the temperature at that depth was greater than the 727°C transformation temperature. Secondly, since it had been established that the thermal excursion on the lower head due to the accident was of the order of 30 minutes, prior austenite grain size at the bottom-most tip of the heat-affected samples was compared with the prepared standards given the 30-minute heat treatments. The results of this rough analysis indicated that the temperature 50 mm from the inside surface (45 mm from the stainless steel/low alloy steel interface) was approximately 50 to 150°C lower than the peak temperatures determined previously for the region near the interface. There is a fair amount of uncertainty in the gradient estimate since only average prior austenite grain size was used for the determination and that measurement cannot be made with precision. Also, the assumption that 30 minutes was the actual time at peak temperatures 50 mm into the thickness may be in error.

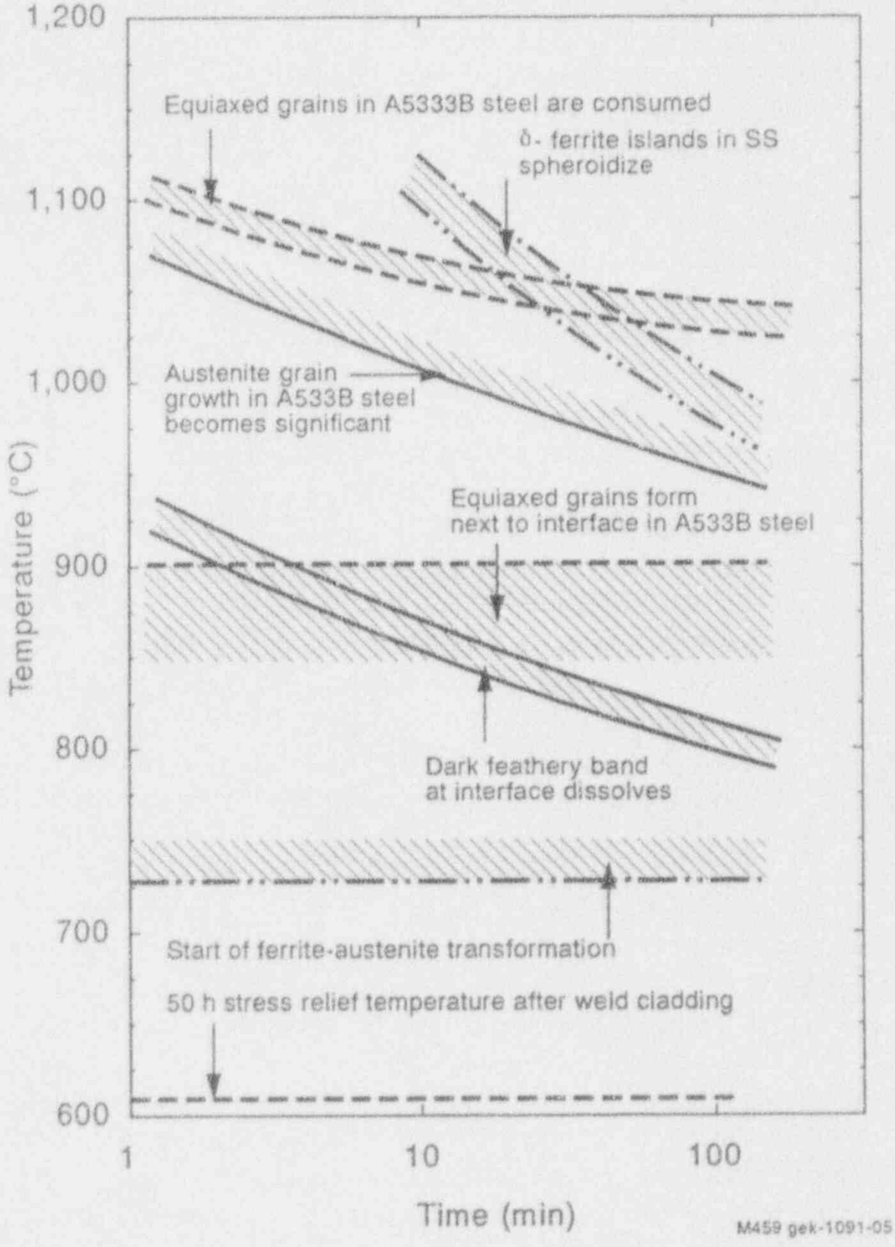


Figure 11. Diagram of time/temperature observations of A533B pressure vessel steel clad with Type 308L stainless steel.

CONCLUSIONS

From this investigation, the following conclusions can be made concerning the thermal history of the TMI-2 steel samples extracted from the lower head.

1. Of the thirteen full section and two partial section samples received at the INEL, only F-10(m-3), E-8(m-3), G-8(m-1), and E-6(m-1) have shown hardness values indicative of having exceeding 727°C (1,000 K).

2. A feathery dark band right at the low alloy steel/stainless steel cladding interface starts to dissolve at temperatures of the order of 900°C at times of 10 minutes and longer. Carbon diffusion from the low alloy steel into the stainless steel weld cladding is evident in the accident heat-affected samples and is undoubtedly the mechanism for the dissolution of the feathery carbide band and the formation of the cementite-devoid equiaxed grains.

3. At a temperature of 1,000°C and a time of 100 minutes, or a temperature of 1,100°C and a time of 10 minutes, the carbides dissolve at the ferrite/austenite boundaries of the stainless steel cladding and the δ-ferrite islands change their morphology.

4. Grain growth of the low alloy steel starts to become significant at 1,000°C and, therefore, prior austenite grain size is another indicator of temperature.

5. Using the combination of microstructure from the stainless steel weld cladding, the pressure vessel steel austenite grain size and morphology, the interface, and carbon diffusion distance into the stainless steel, comparisons with standards of known thermal histories showed that Sample F-10(m-3) experienced 1,040 to 1,060°C for approximately 30 minutes during the accident and Sample E-8(m-3), 1,075 to 1,100°C for about 30 minutes.

6. Although the stainless steel cladding and the stainless steel/low alloy steel interface were not available at INEL for Samples G-8(m-1) and E-6(m-1), based on the hardness and microstructure of the low alloy steel and the hot cell micrographs from ANL that did show the interface and stainless steel cladding, the G-8 position experienced temperatures during the accident approximately the same as F-10(m-3) (1,040 to 1,060°C for 30 min) and the E-6 position was approximately the same as E-8(m-3) (1,075 to 1,100°C for 30 minutes).

7. The temperatures at 50 mm from the inside surface (45 mm from the weld cladding/low alloy steel interface) were estimated to be 100±50°C lower than the peak temperatures.

REFERENCES

1. R. L. Moore and E. L. Tolman, *Estimated TMI-2 Vessel Thermal Response Based on the Lower Plenum Debris Configuration*, Joint AIChE/ASME Heat Transfer Conference, High Melt Attack Phenomena Session, Houston, TX, July 27, 1988.

2. D. R. Diercks, *TMI-2 Vessel Investigation Project (VIP) Metallurgical Program*, Progress Report January-September 1989, NUREG/CR-5224, ANL-90/2, Vol. 1, March 1990.

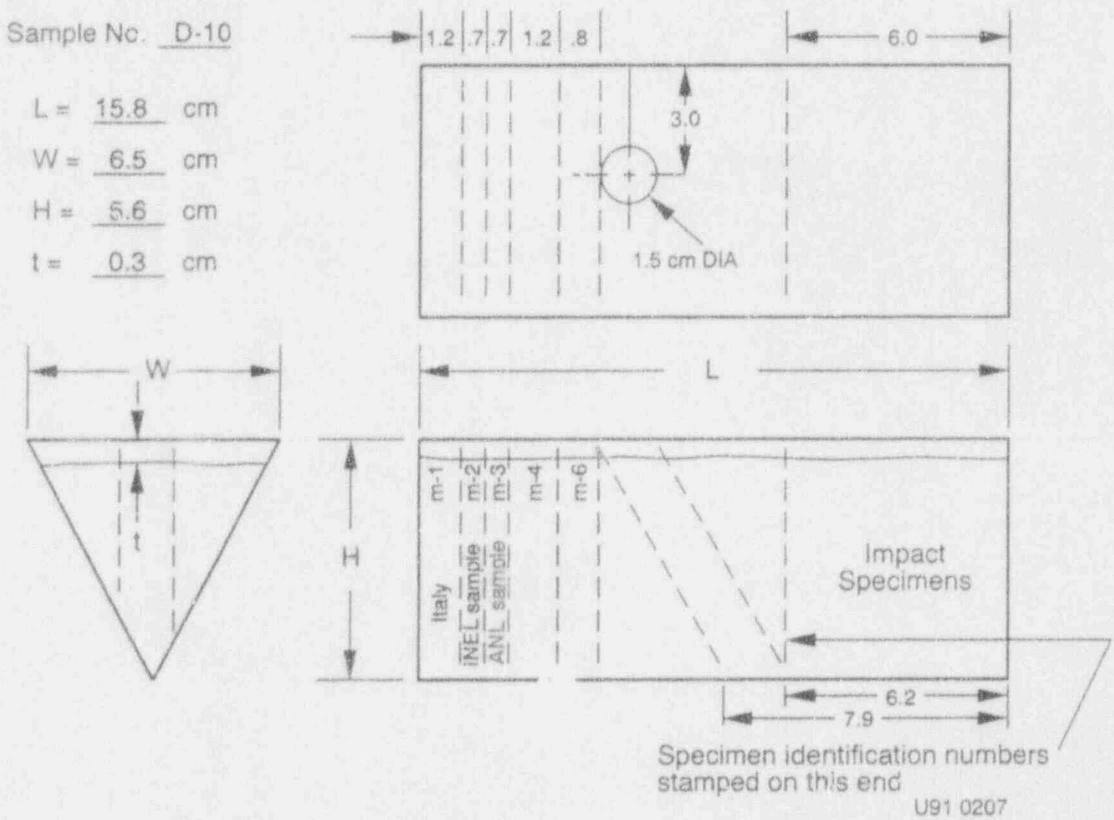
3. R. Tricot and R. Castro, "Study of the Isothermal Transformations in 17% Cr Stainless Steels," *The Metallurgical Evolution of Stainless Steels*, ed. by F.B. Pickering, American Society for Metals, Metals Park, Ohio (1979), p. 256.

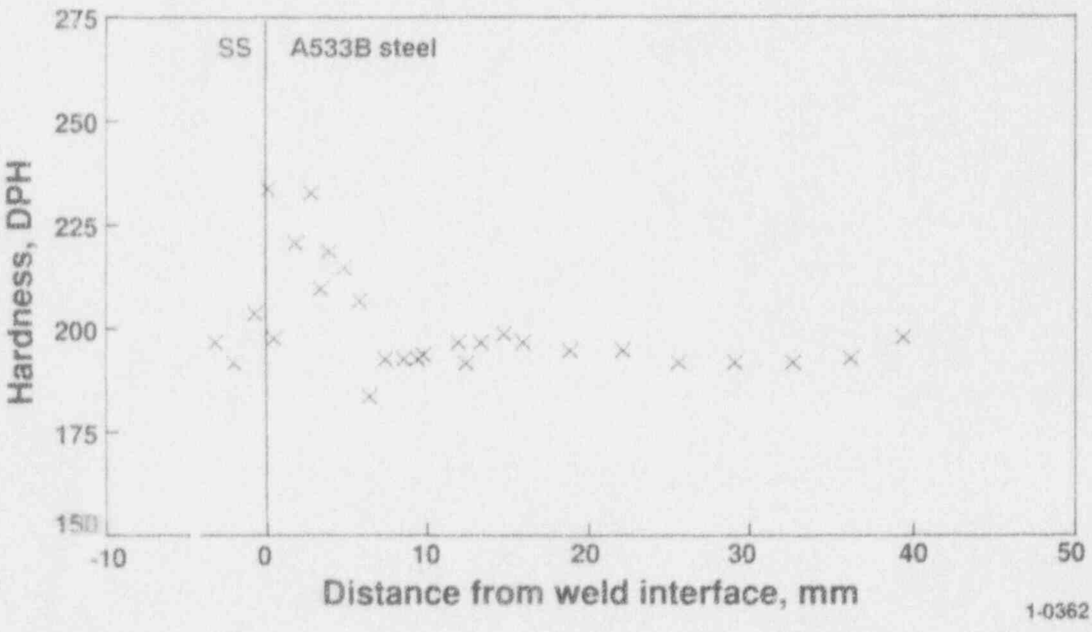
Appendix A

Microstructure and Hardness Profiles of All TMI-2 Metallurgical Samples and Midland Archive Material

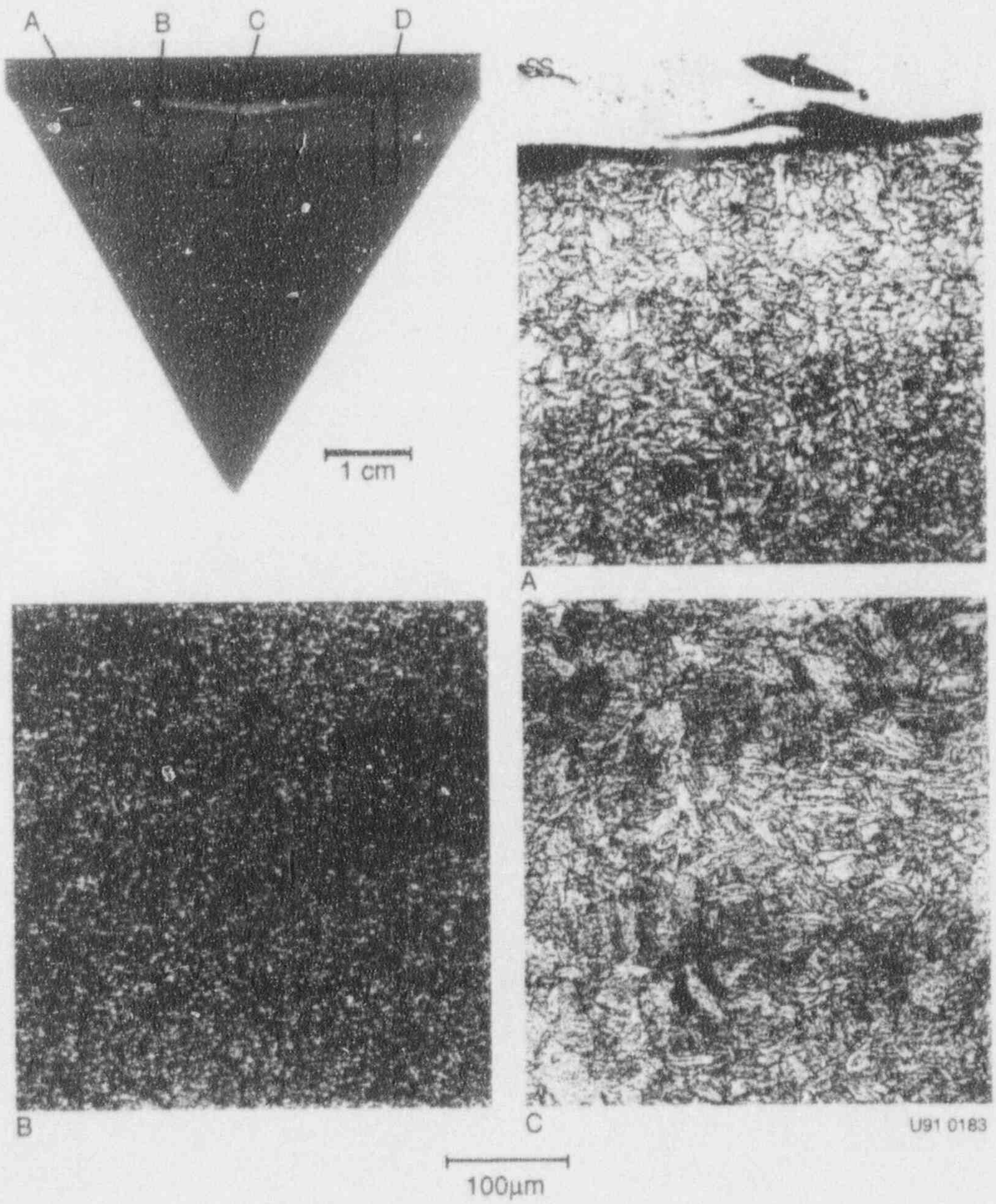
(In alphabetical order)

Sectioning diagram of TMI-2 lower head sample D-10 and hardness profile of INEL subsection D-10 (m-2)

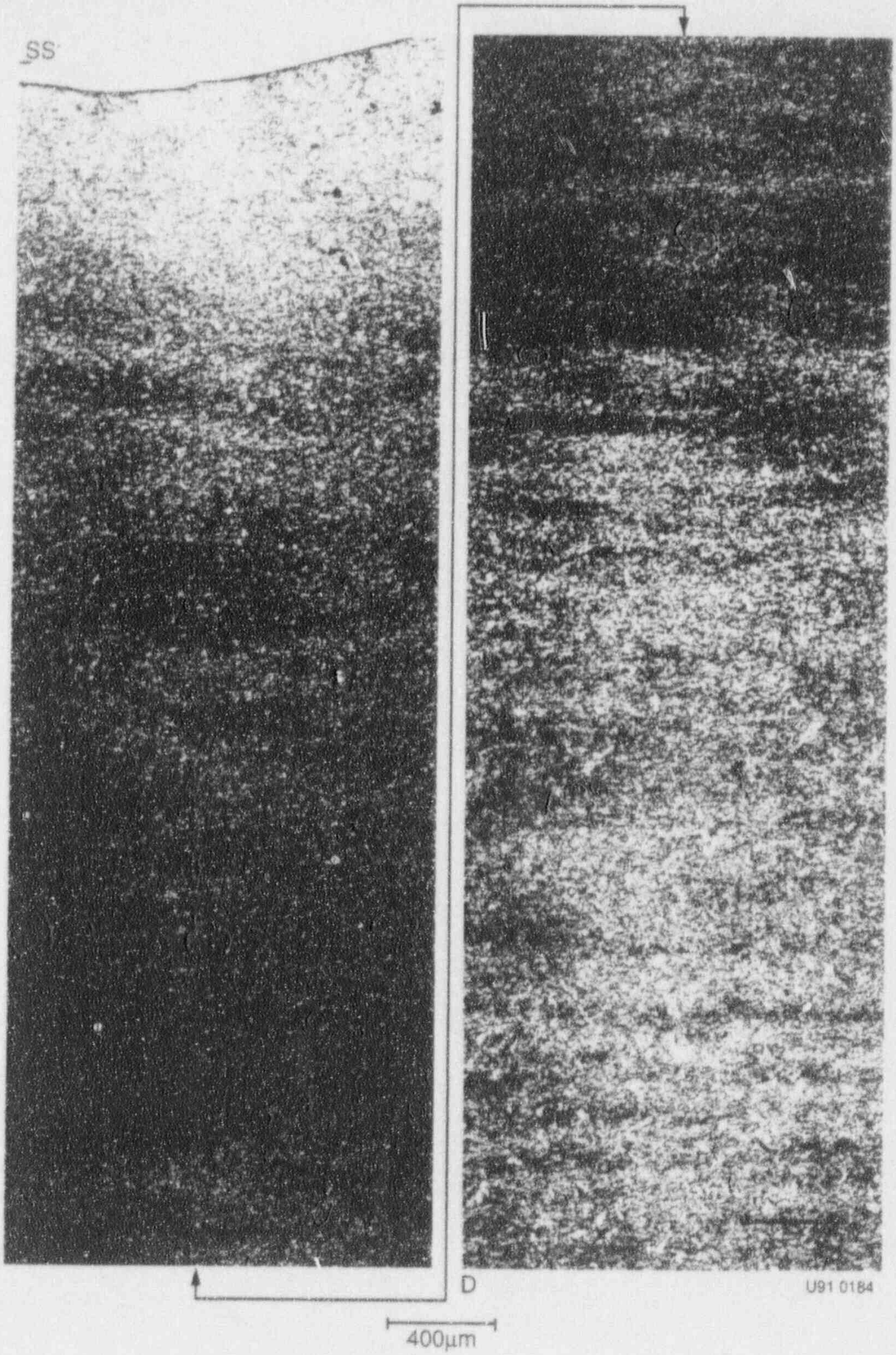




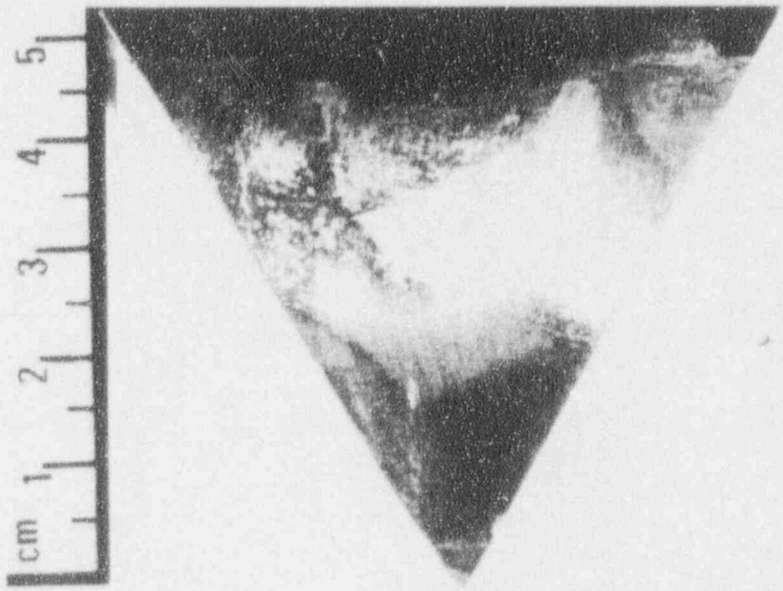
Sample D-10 (m-2)



Sample D-10 (m-2)



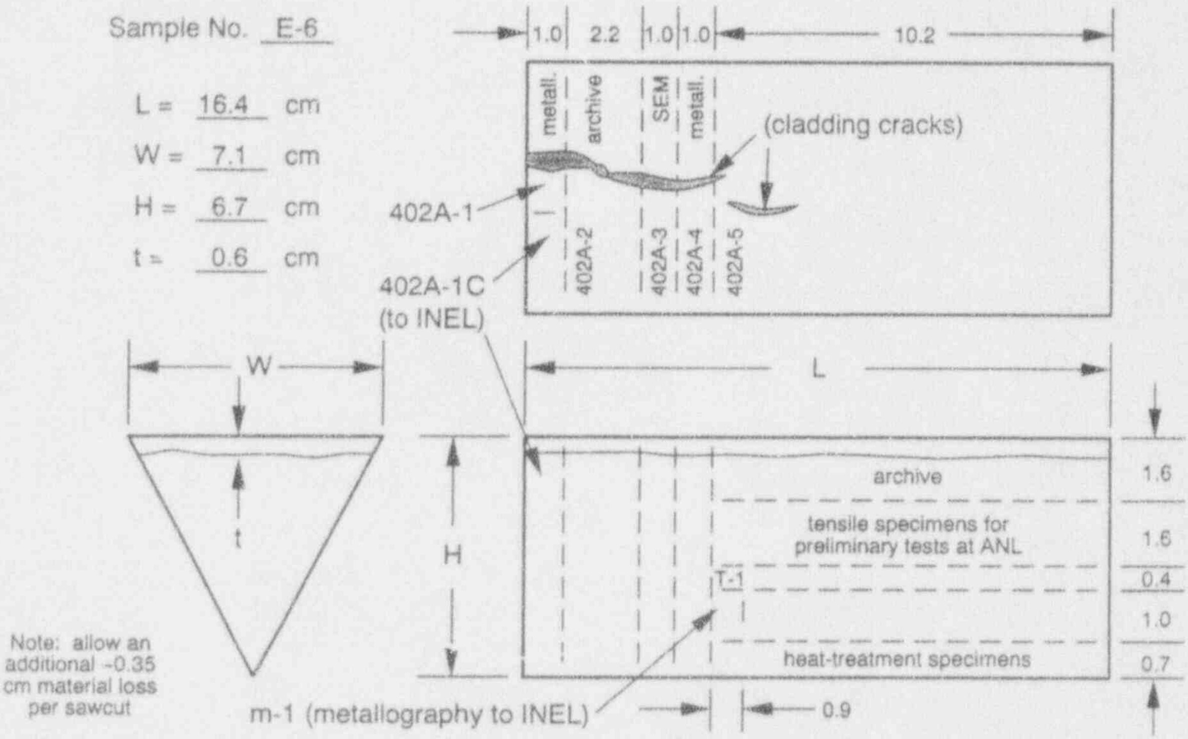
Sample D-10 (m-2)
(backside)



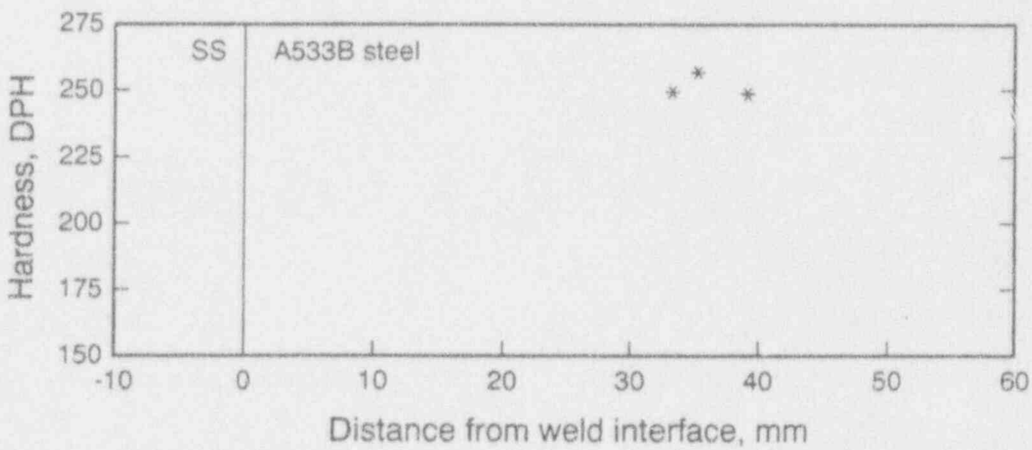
Near nozzle penetration

U91 0185

Sectioning diagram of TMI-2 lower head sample E-6 and hardness profile of INEL subsection E-6 (m-1)



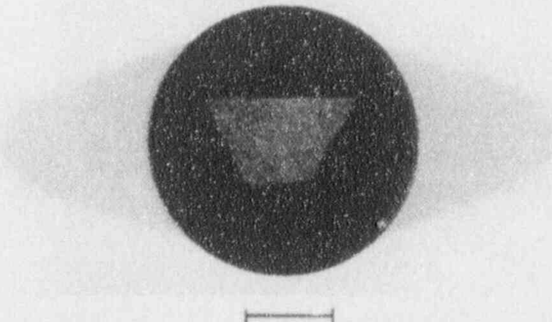
U91 0208



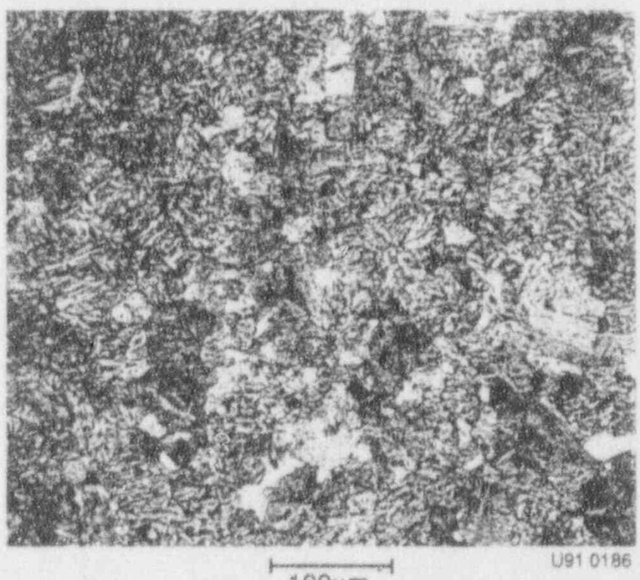
U91 0209

1-0363

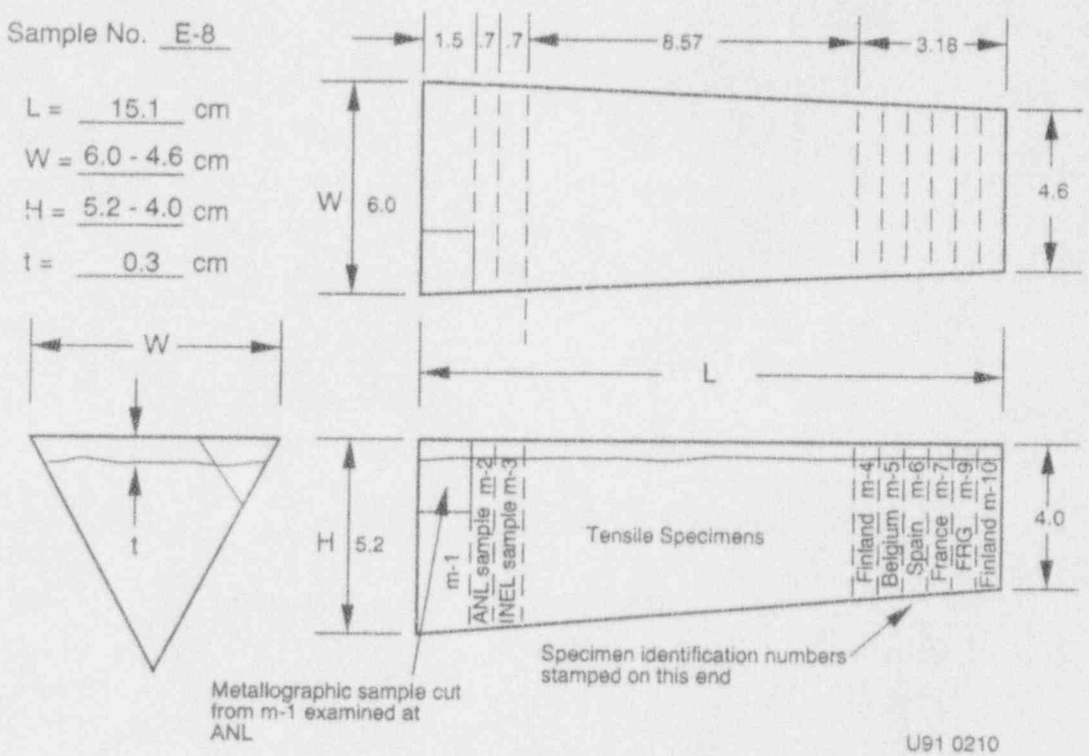
Sample E-6 (m-1)

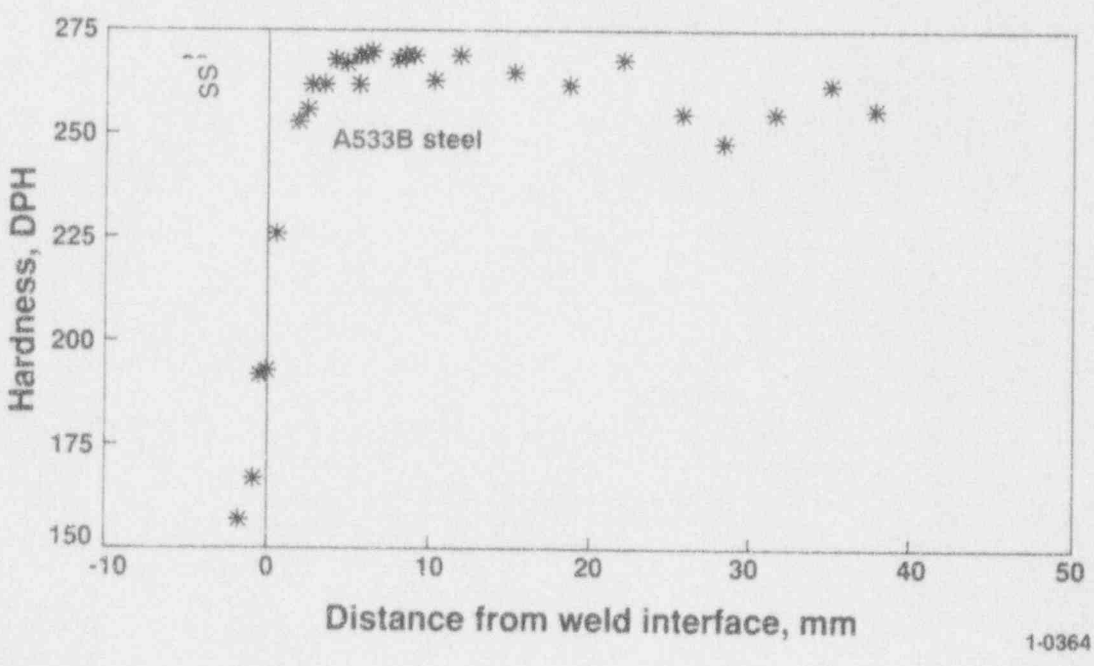


(In met. mount)

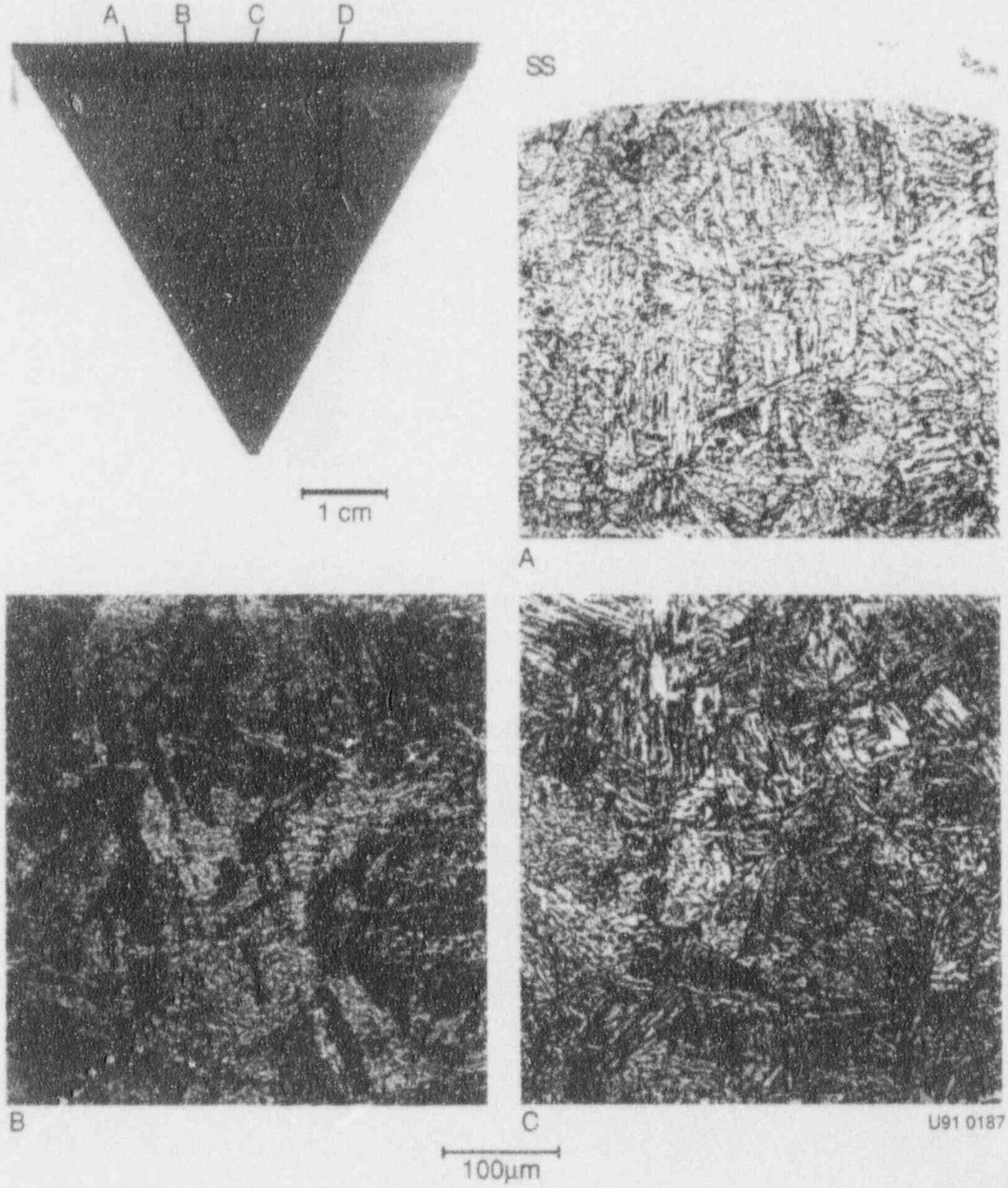


Sectioning diagram of TMI-2 lower head sample E-8 and hardness profile of INEL subsection E-8 (m-3)

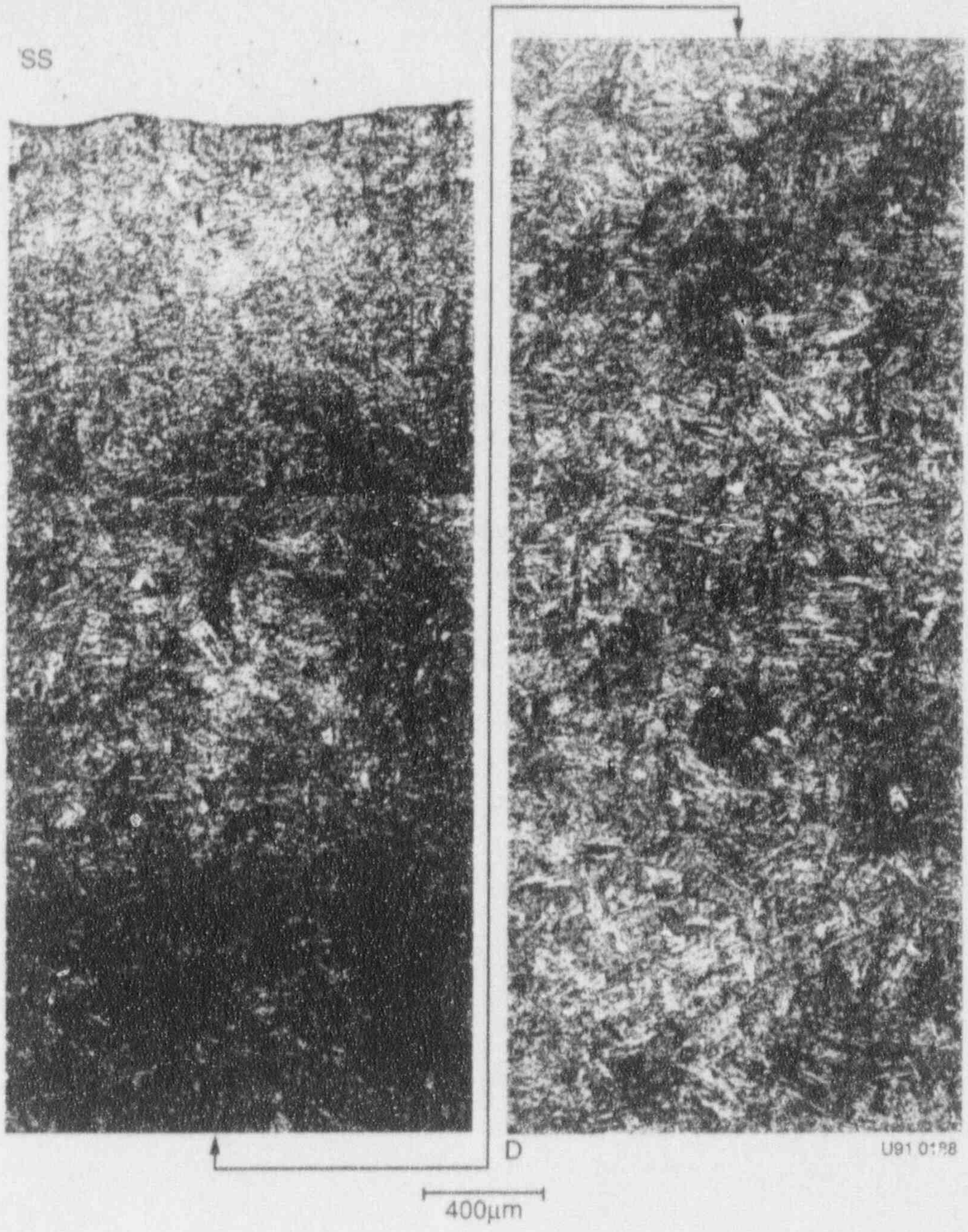




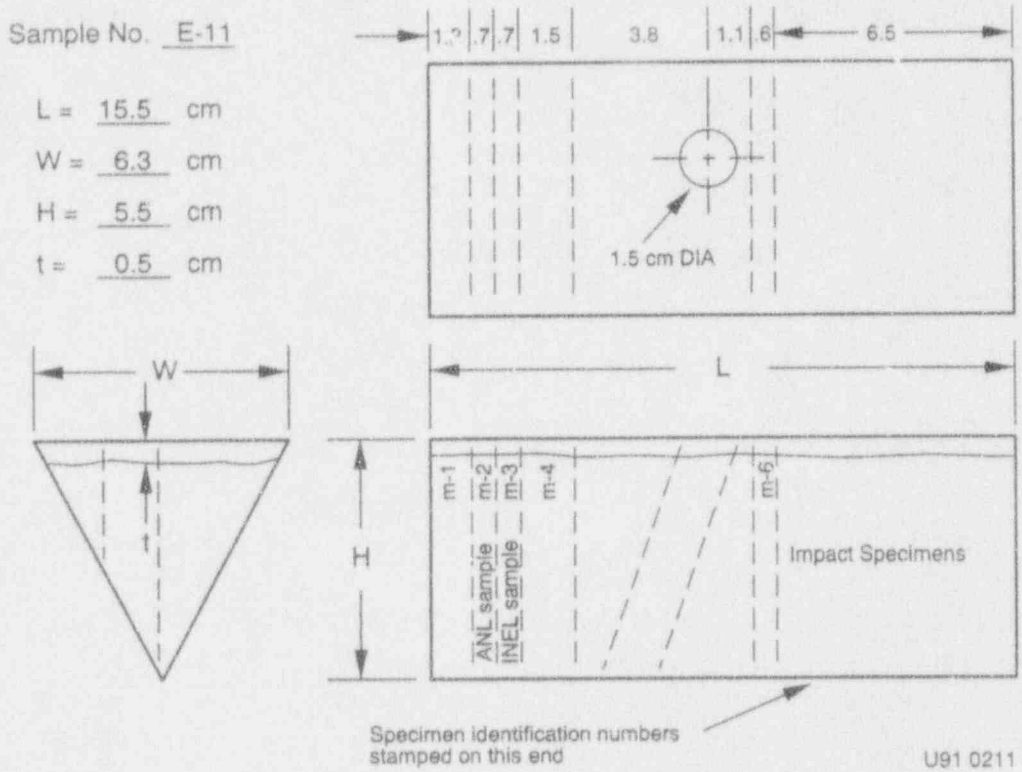
Sample E-8 (m-3)

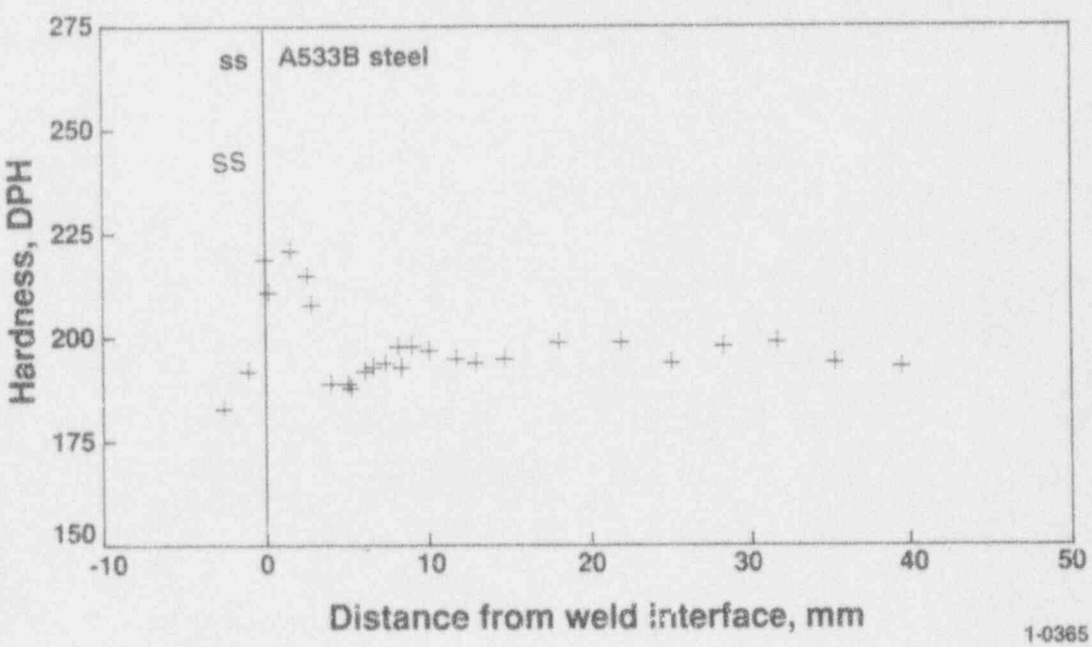


Sample E-8 (m-3)

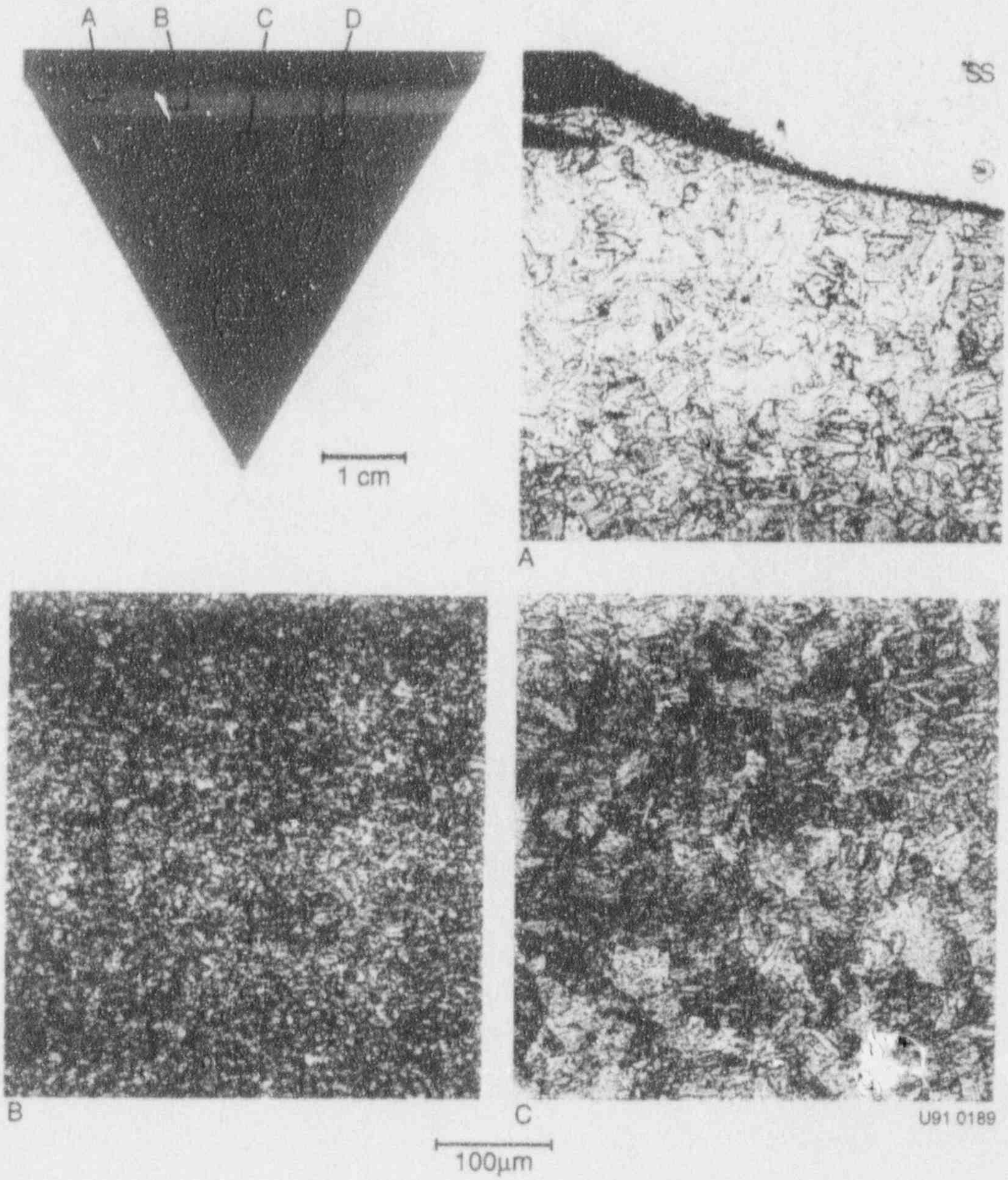


Sectioning diagram of TMI-2 lower head sample E-11 and hardness profile of INEL subsection E-11 (m-3)

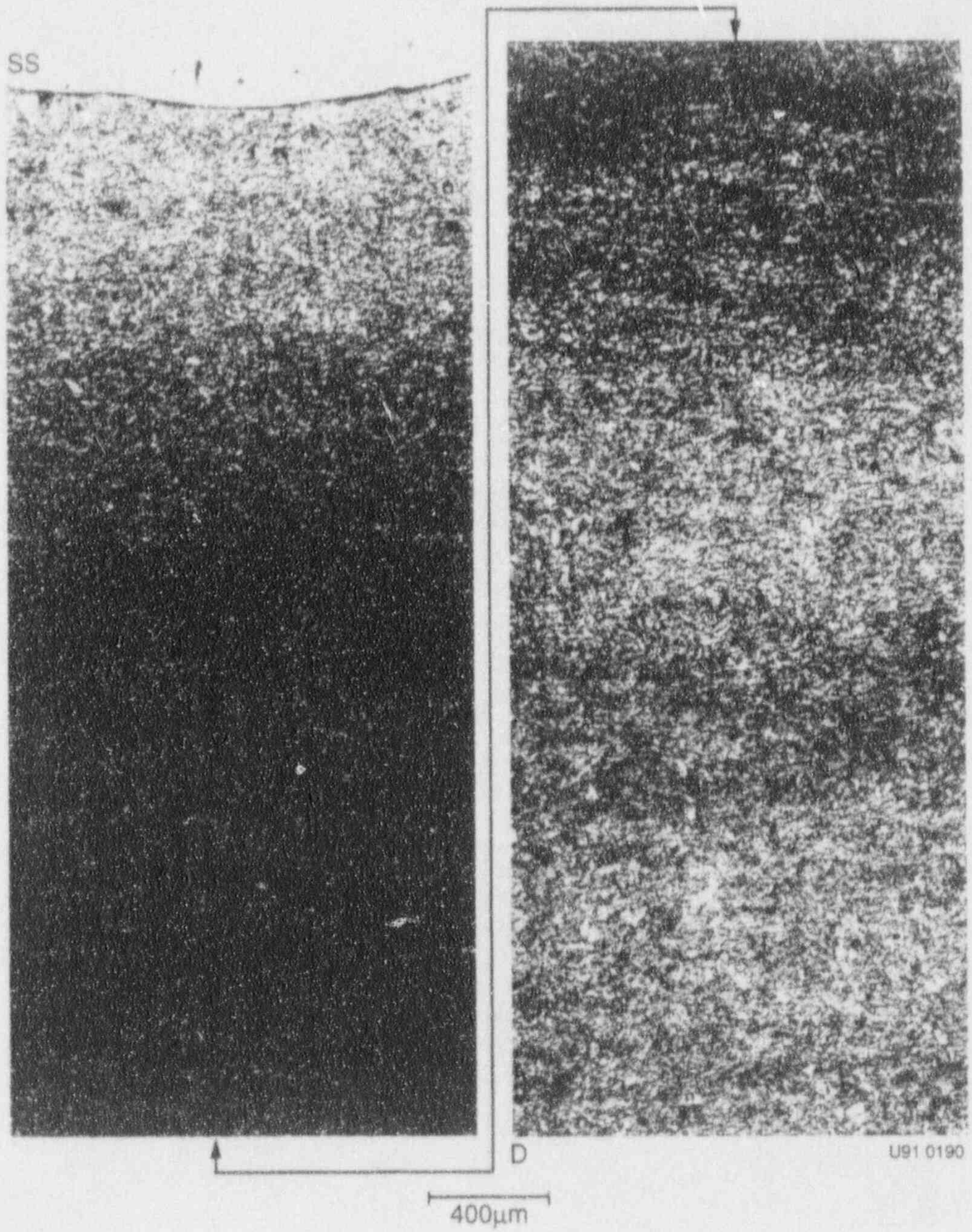




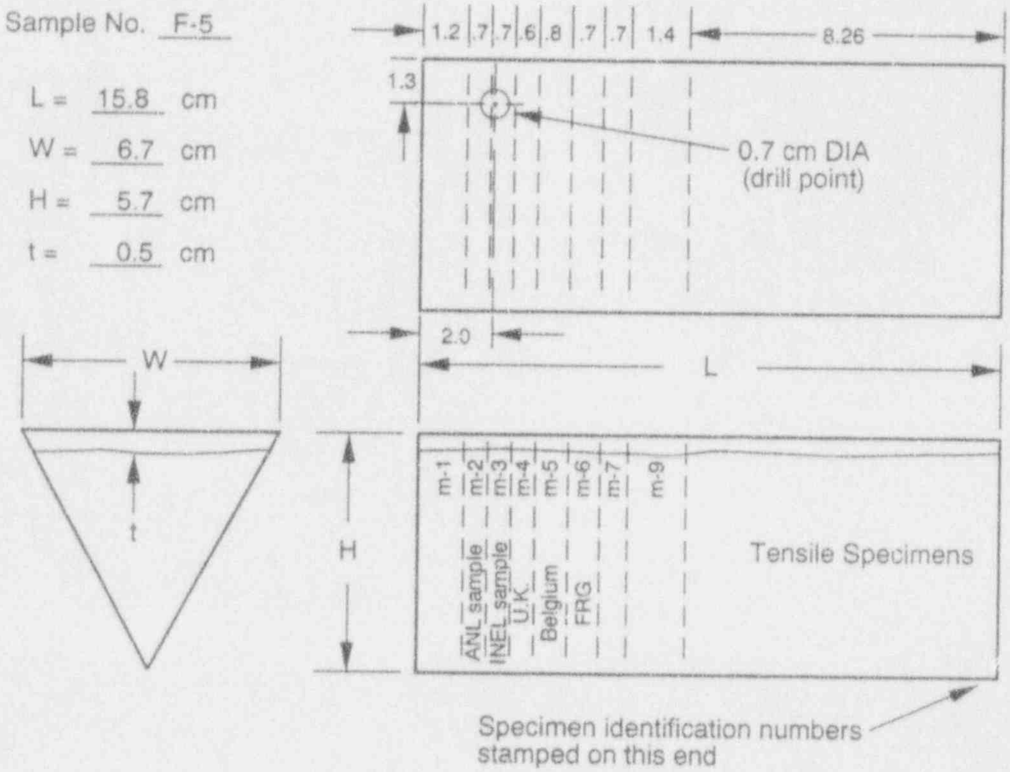
Sample E-11 (m-3)

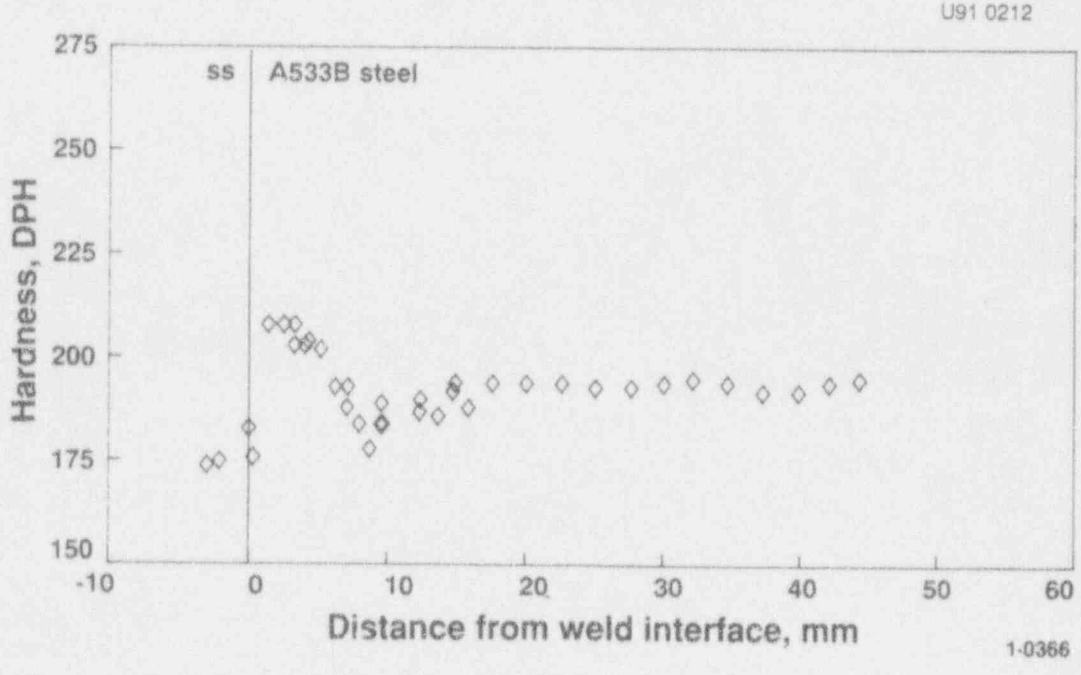


Sample E-11 (m-3)

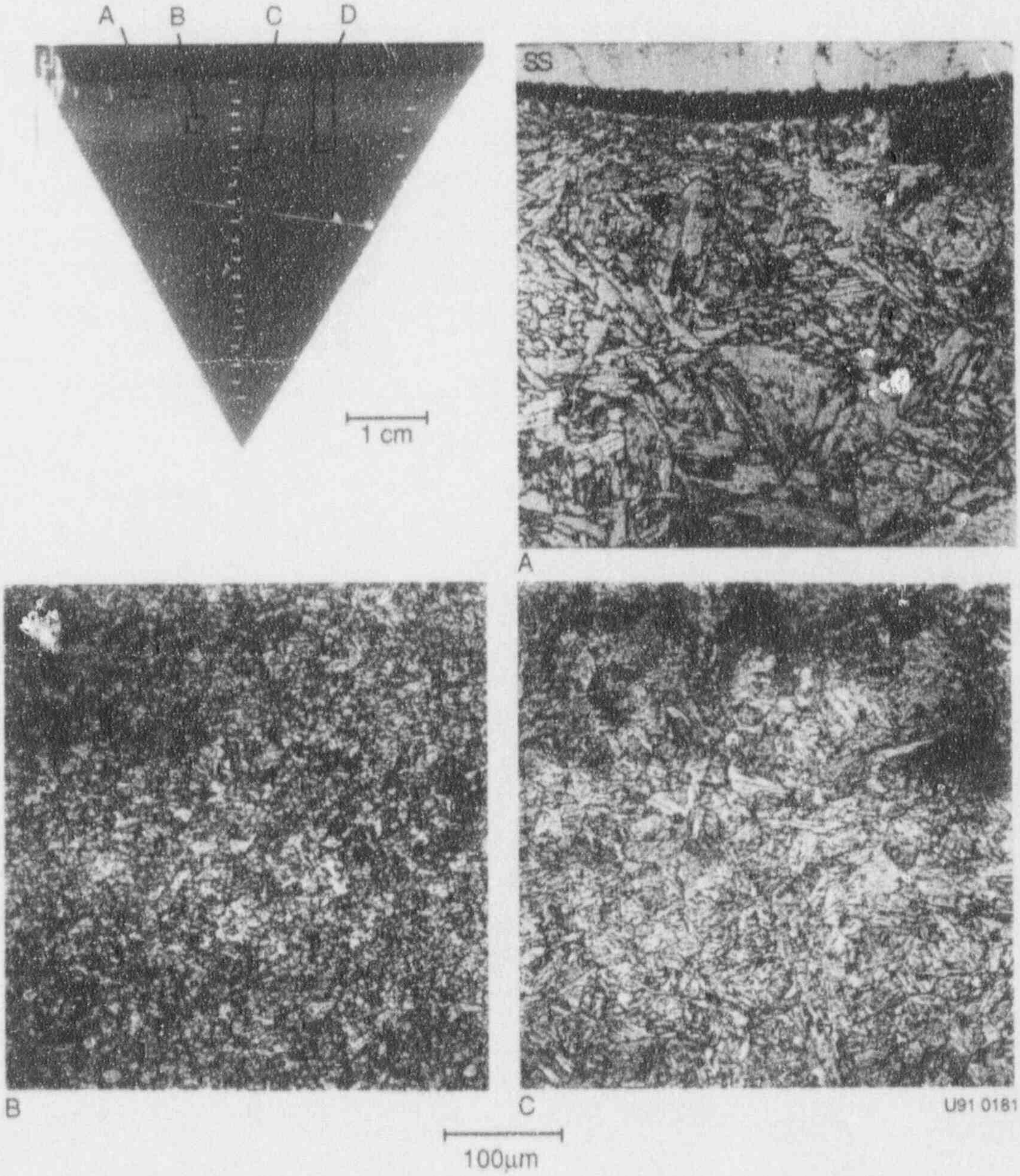


Sectioning diagram of TMI-2 lower head sample F-5 and hardness profile of INEL subsection F-5 (m-3)

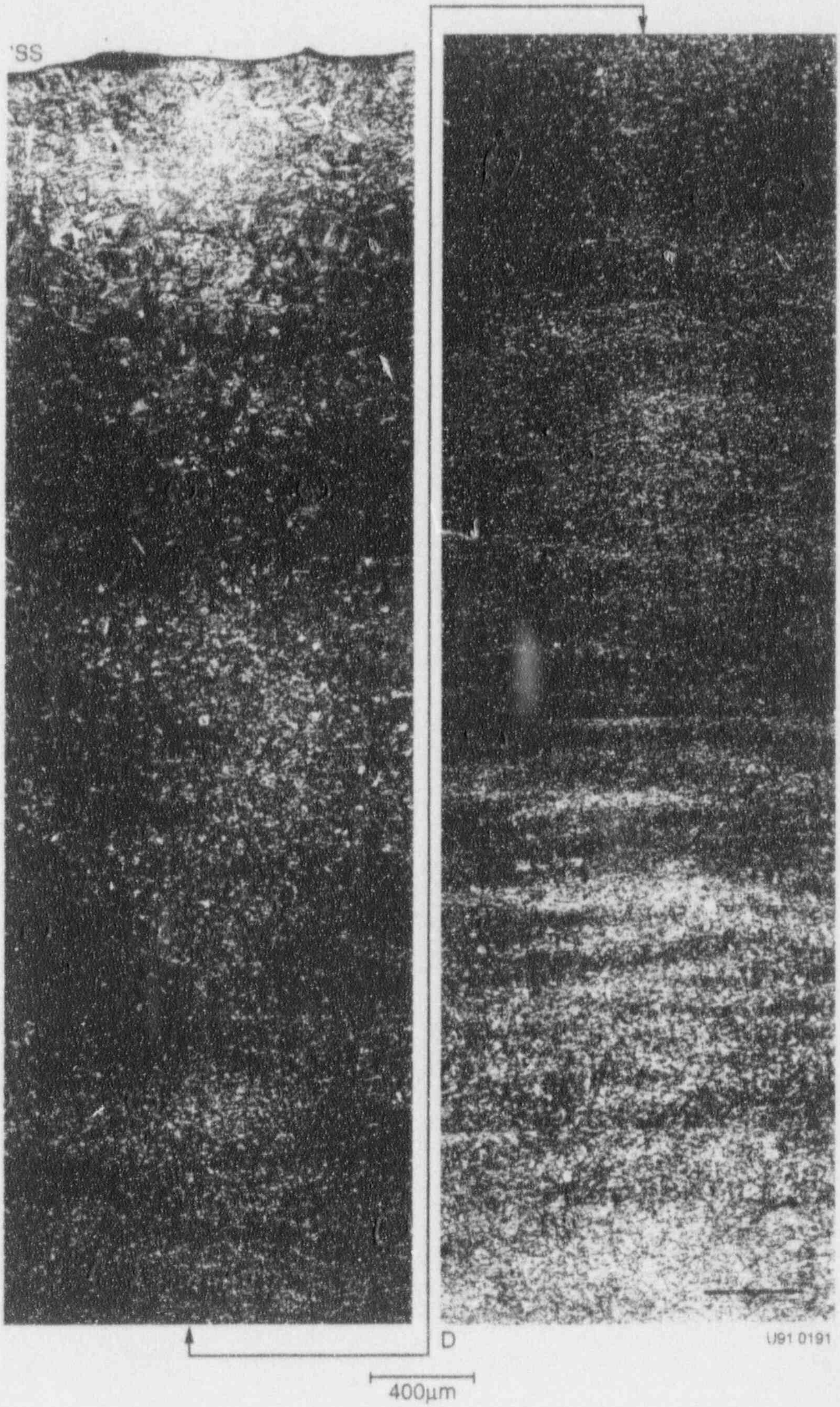




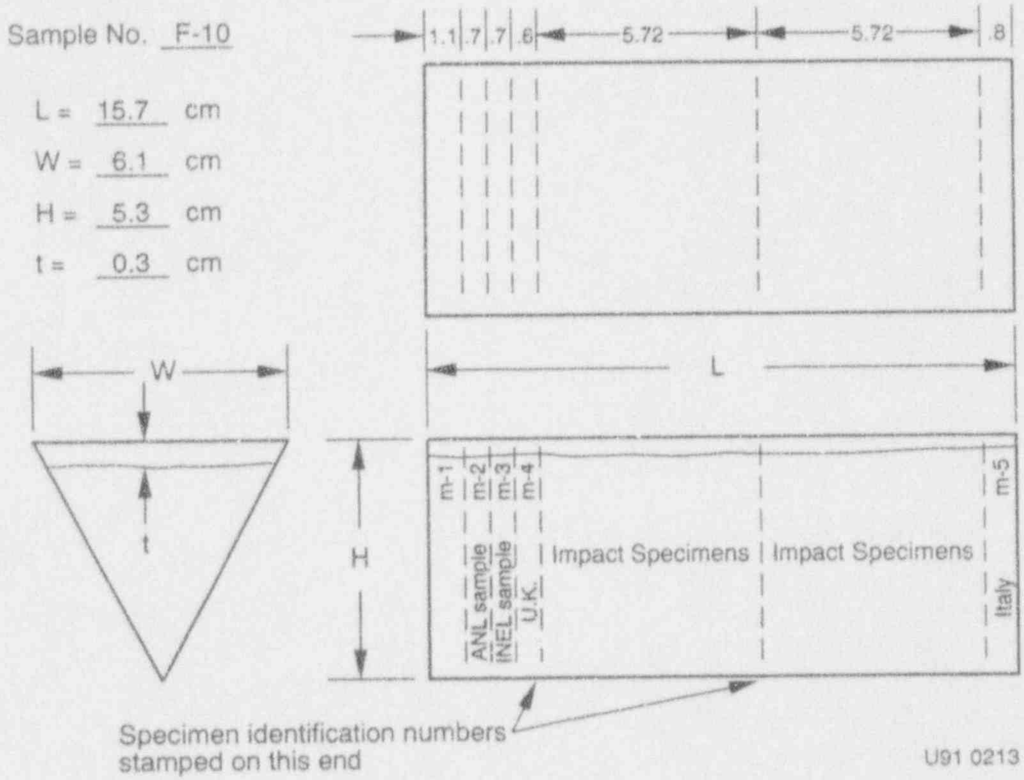
Sample F-5 (m-3)

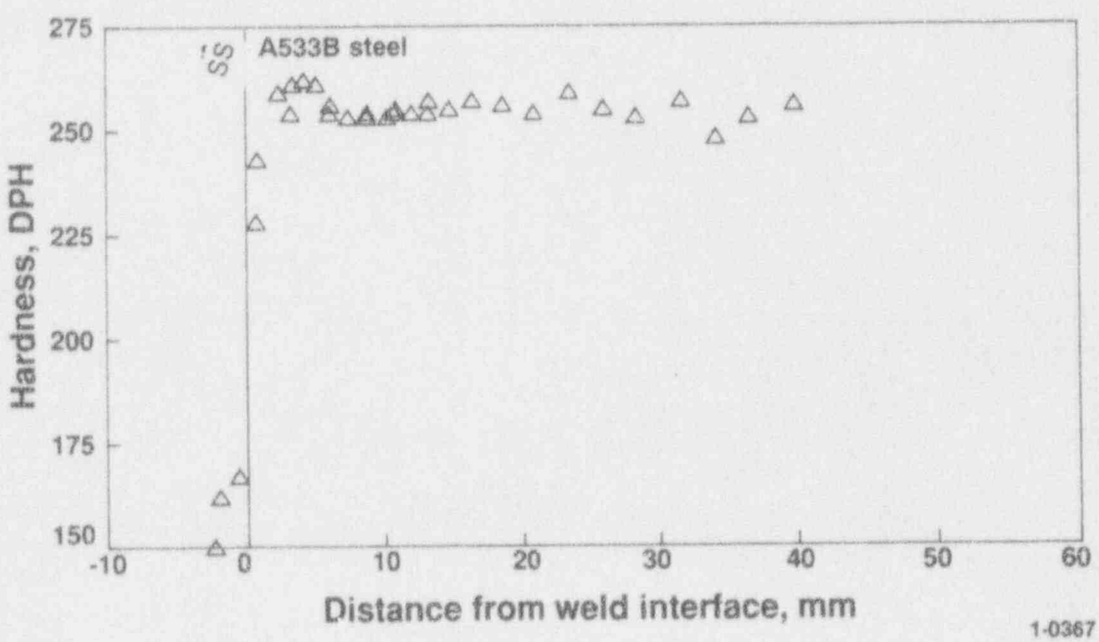


Sample F-5 (m-3)

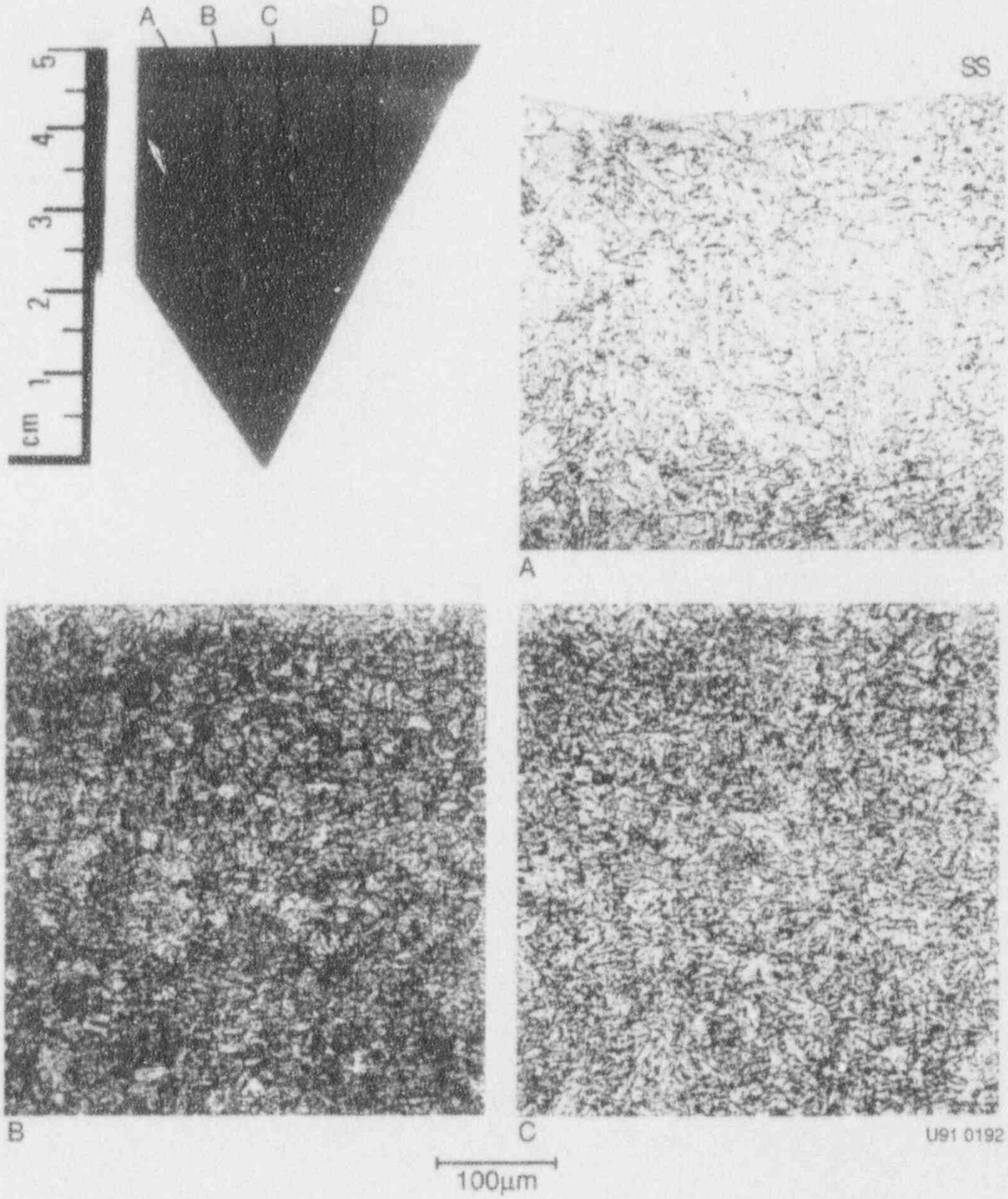


Sectioning diagram of TMI-2 lower head sample F-10 and hardness profile of INEL subsection F-10 (m-3)

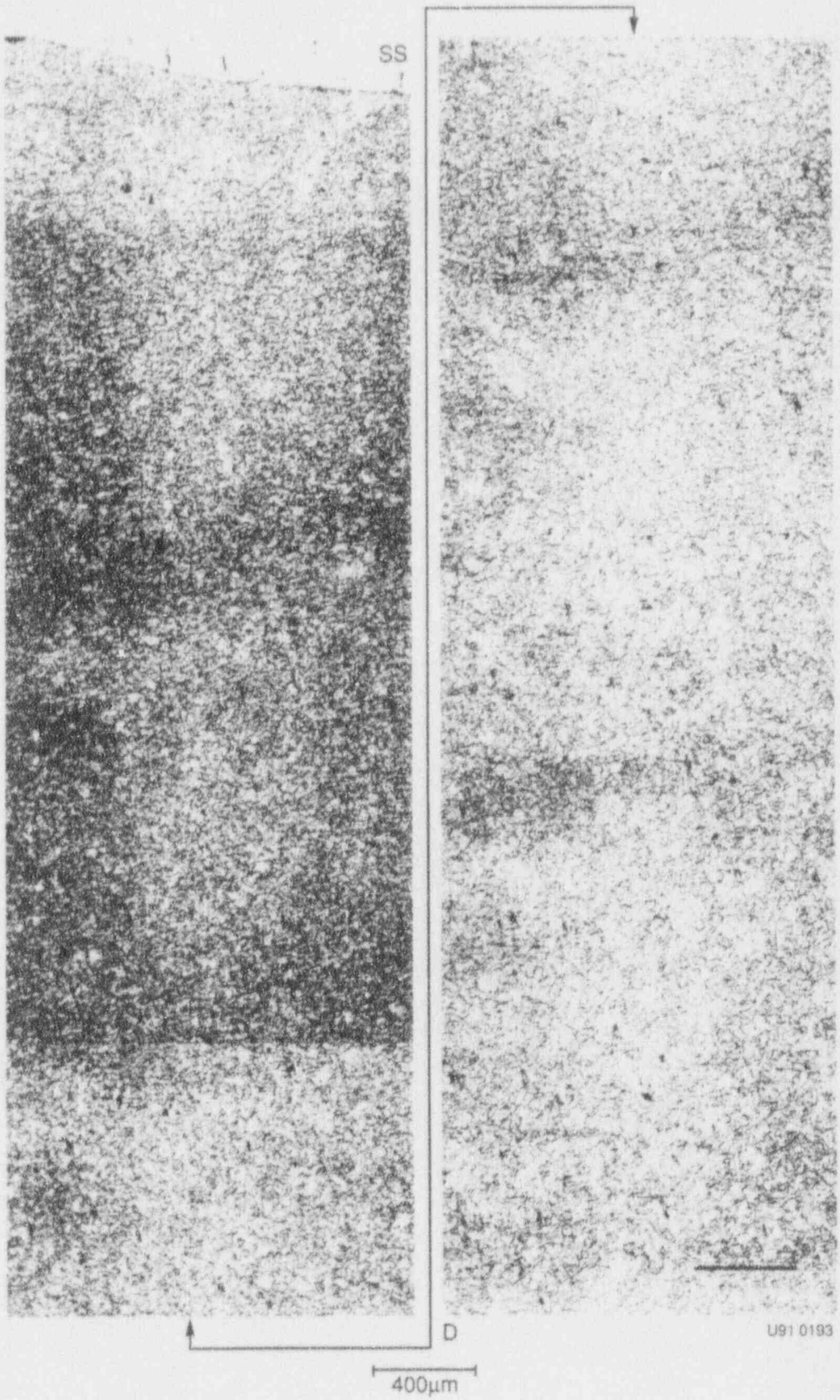




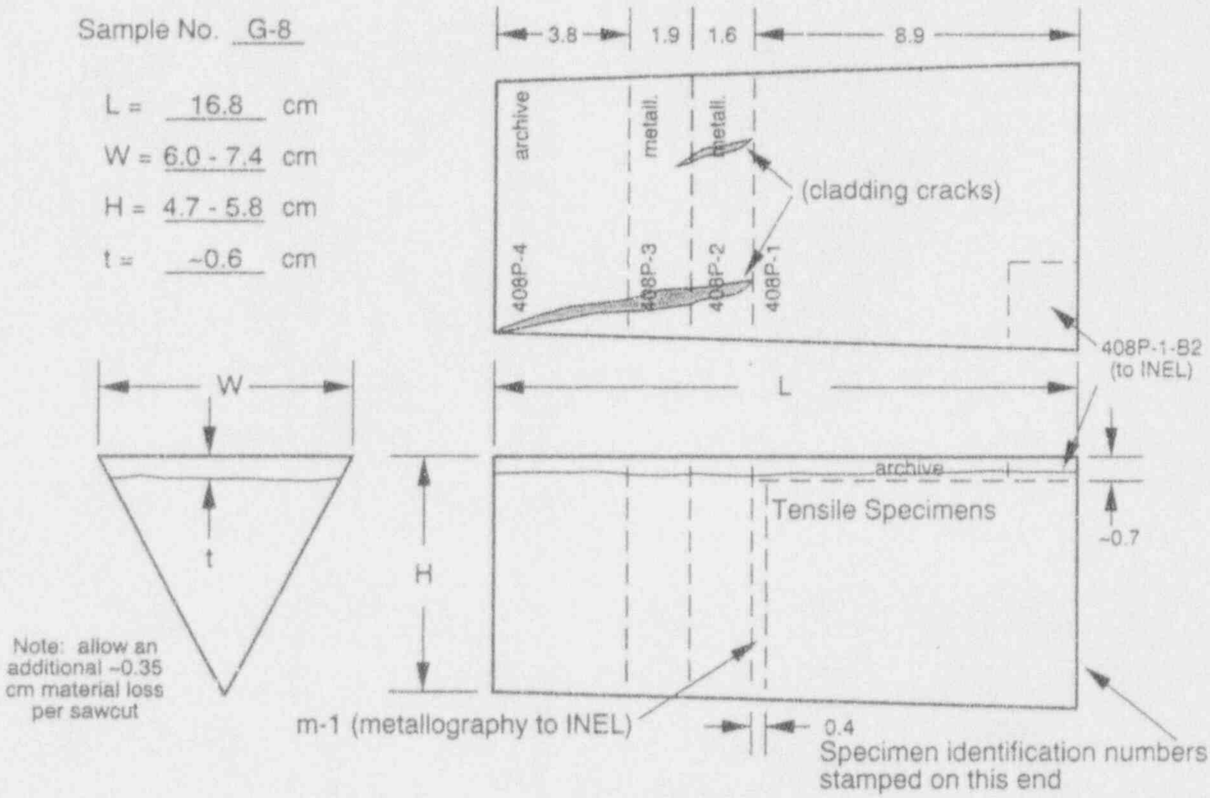
Sample F-10 (m-3)



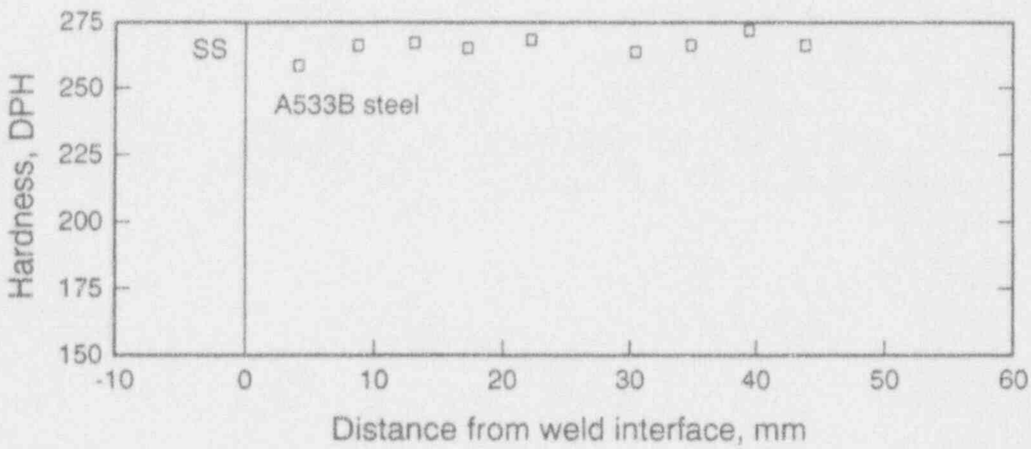
Sample F-10 (m-3)



Sectioning diagram of TMI-2 lower head sample G-8 and hardness profile of INEL subsection G-8 (m-1)



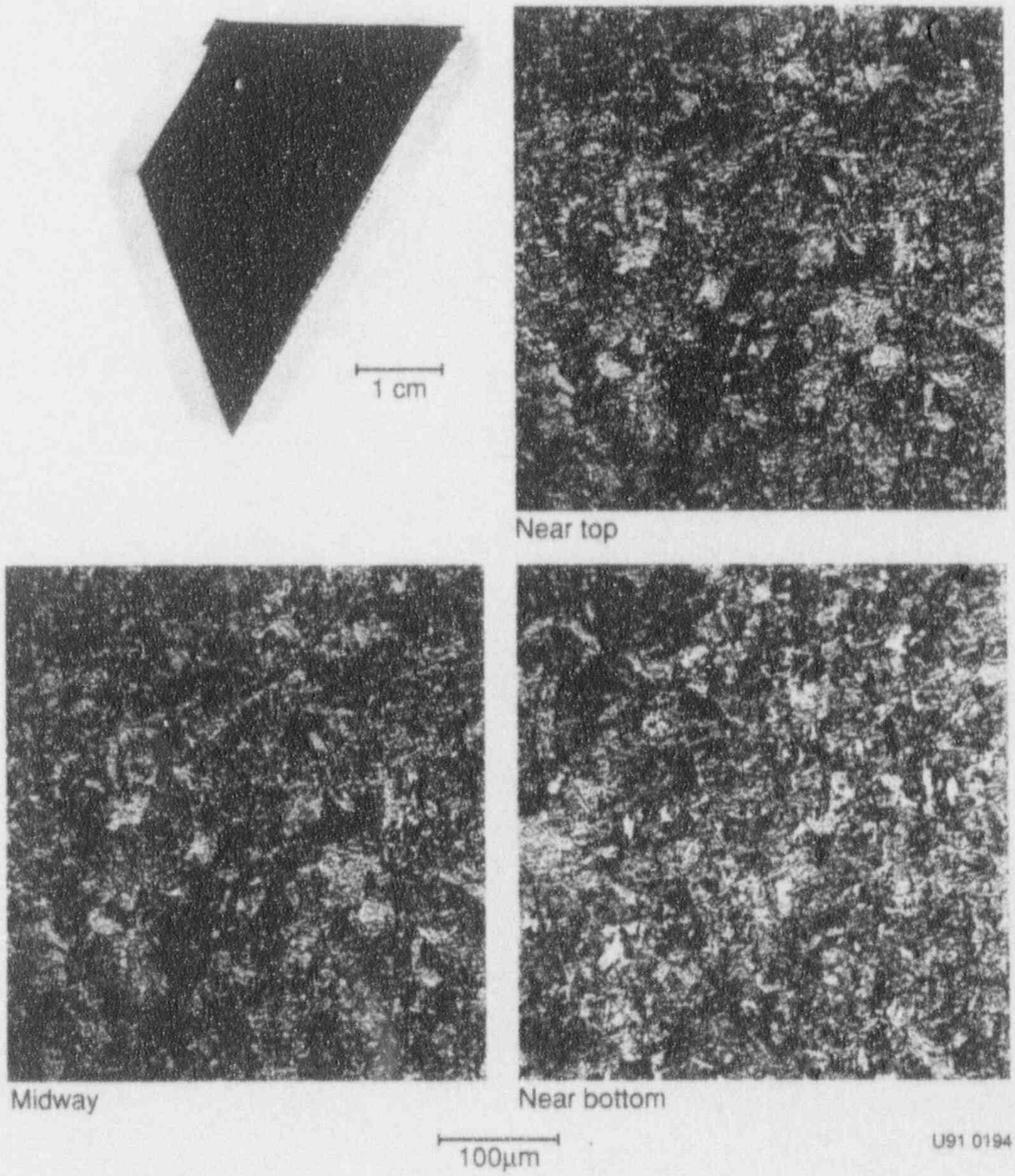
U91 0214



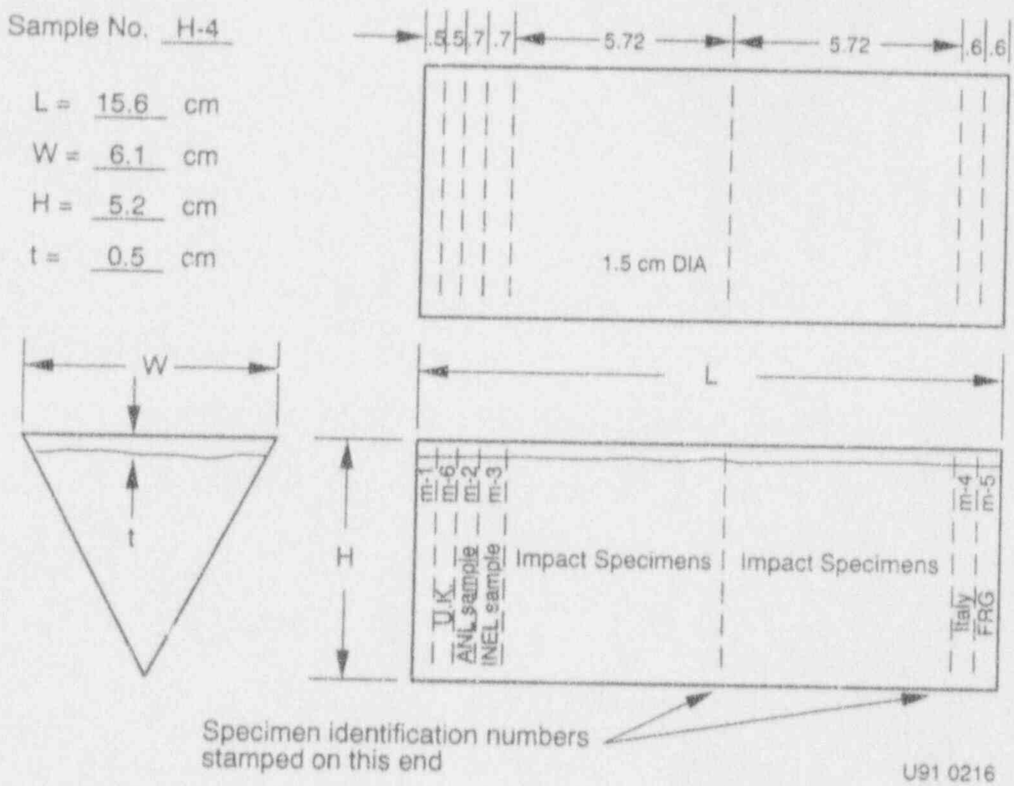
U91 0215

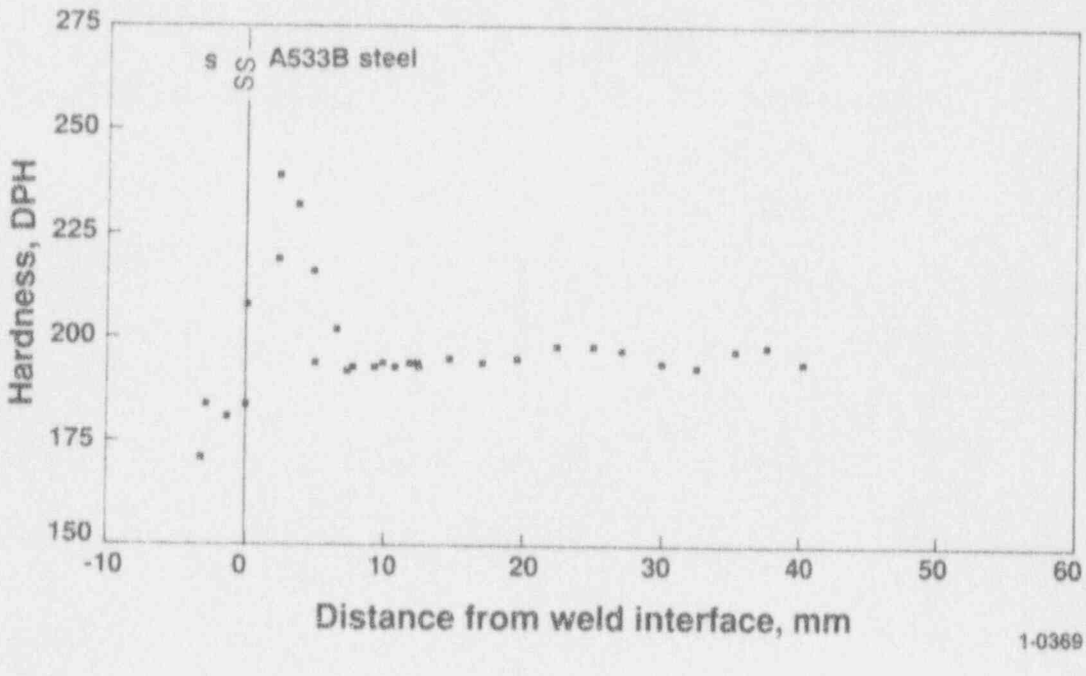
1-0368

Sample G-8 (m-1)

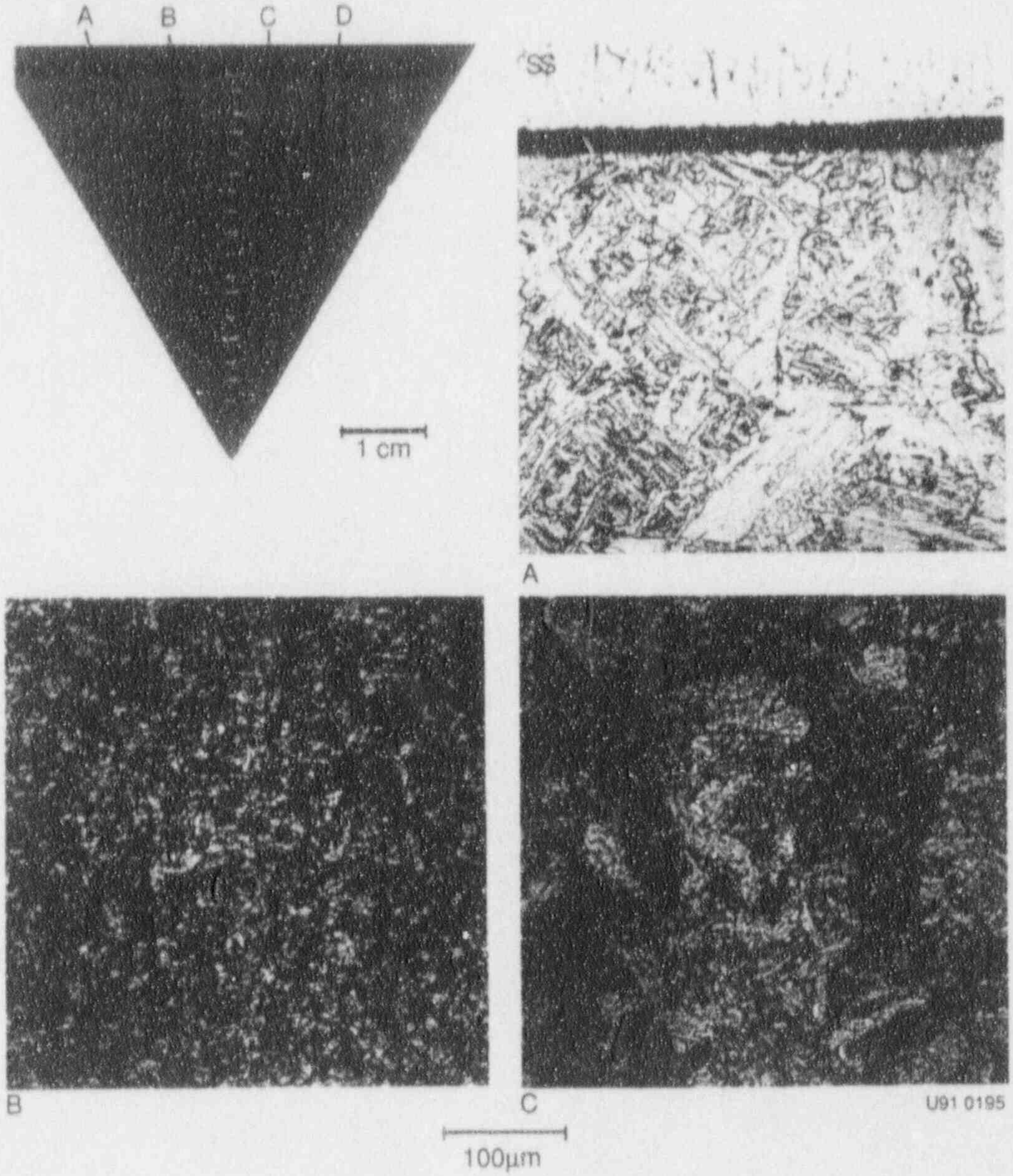


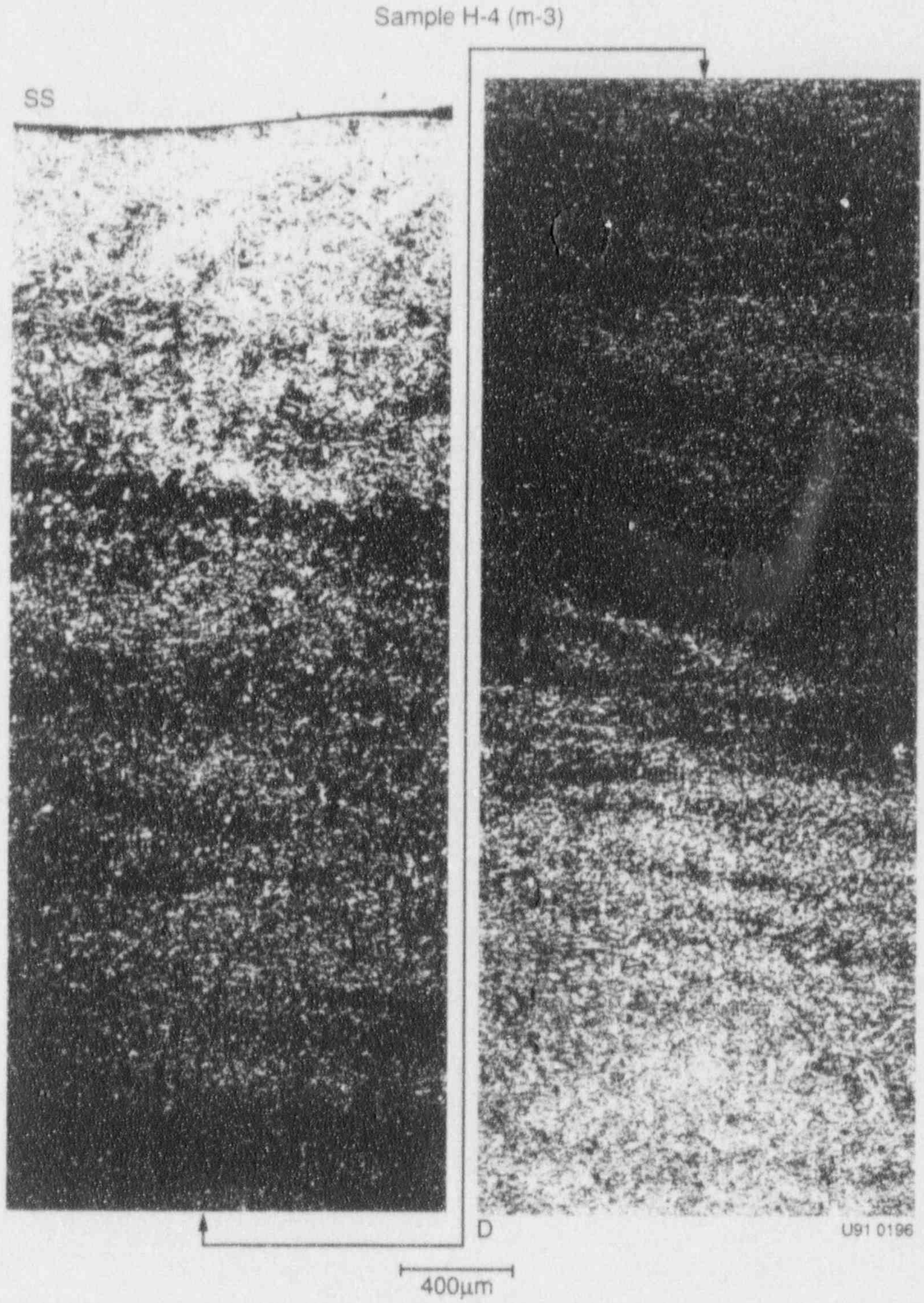
Sectioning diagram of TMI-2 lower head sample H-4 and hardness profile of INEL subsection H-4 (m-3)



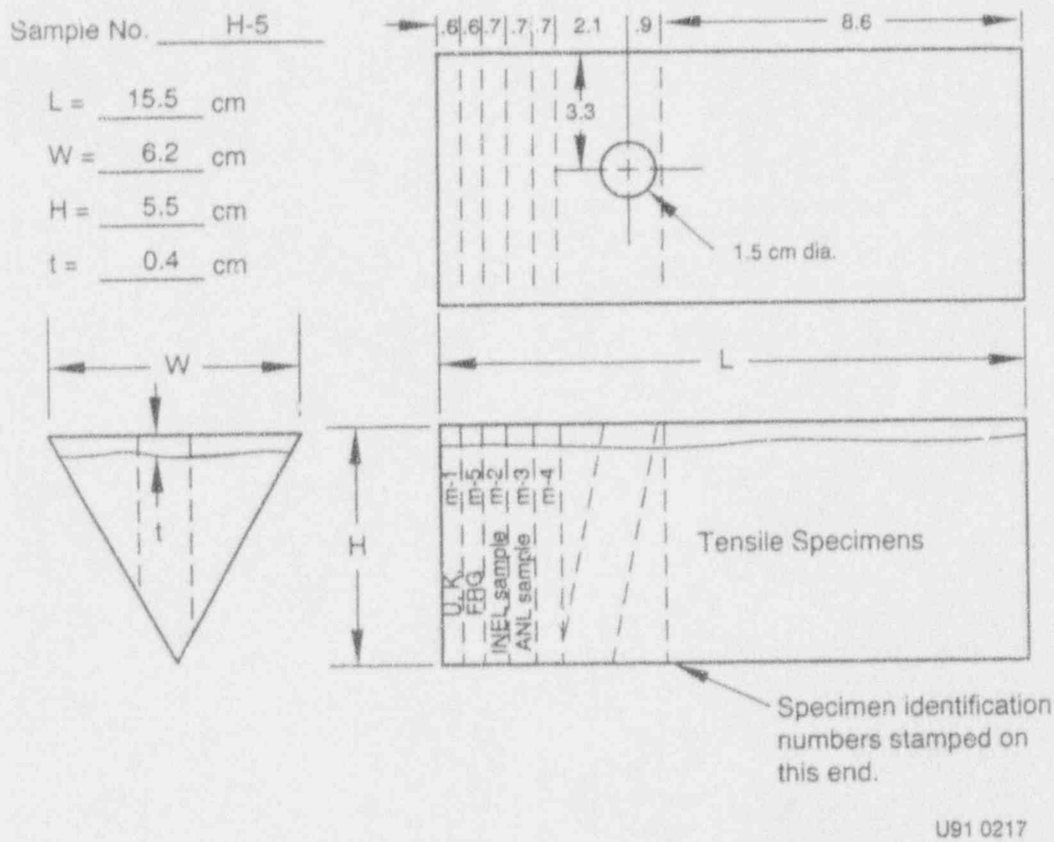


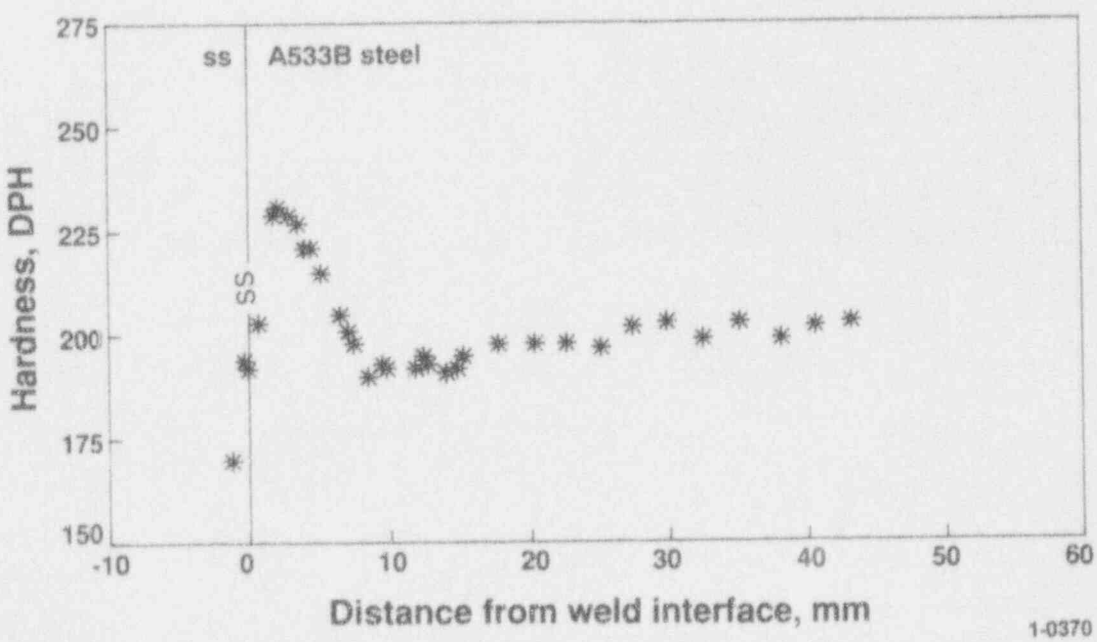
Sample H-4 (m-2)




Sample H-4 (m-3)
SS
D
U91 0196
400μm

Sectioning diagram of TMI-2 lower head sample H-5 and hardness profile of INEL subsection H-5 (m-2)





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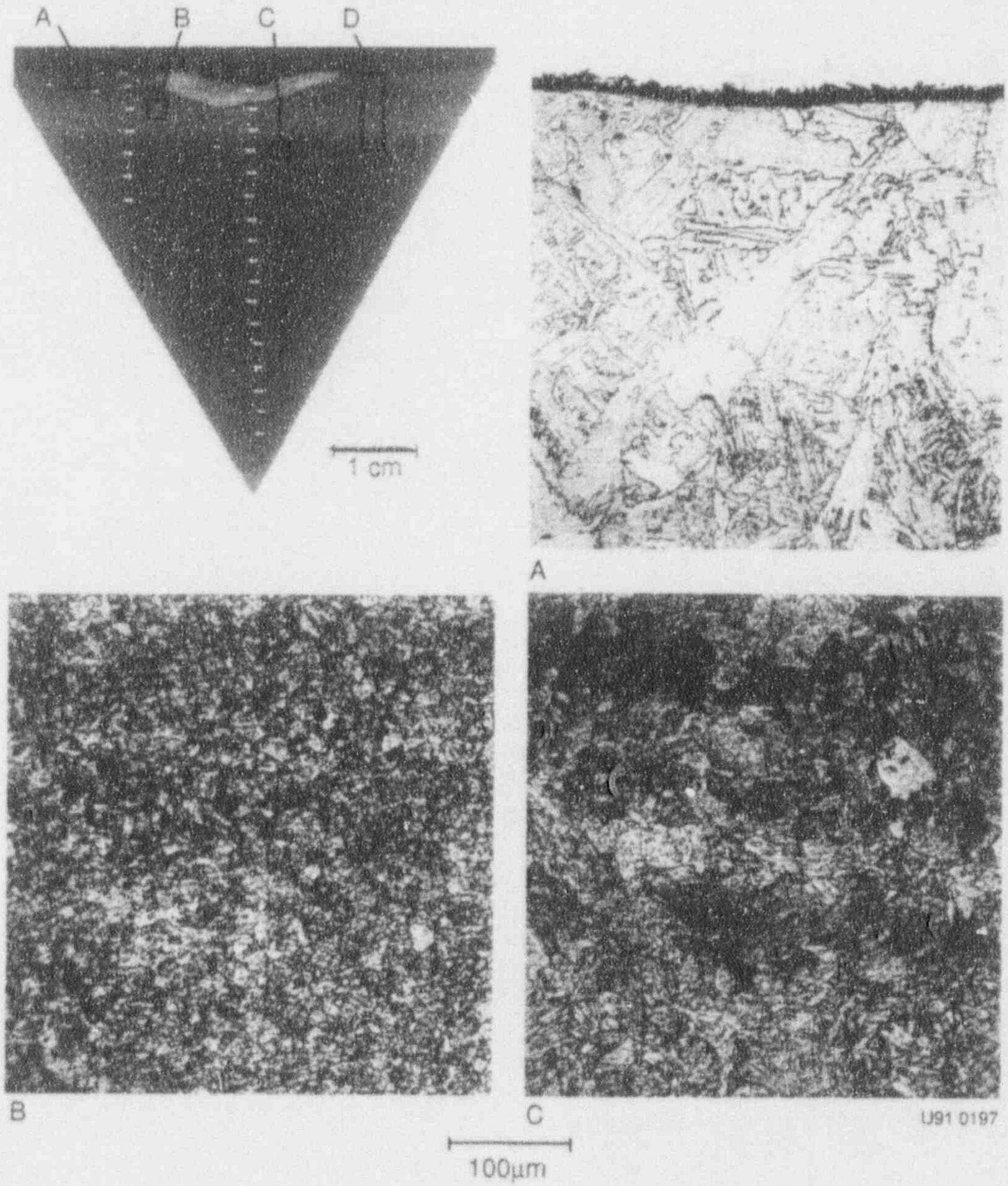

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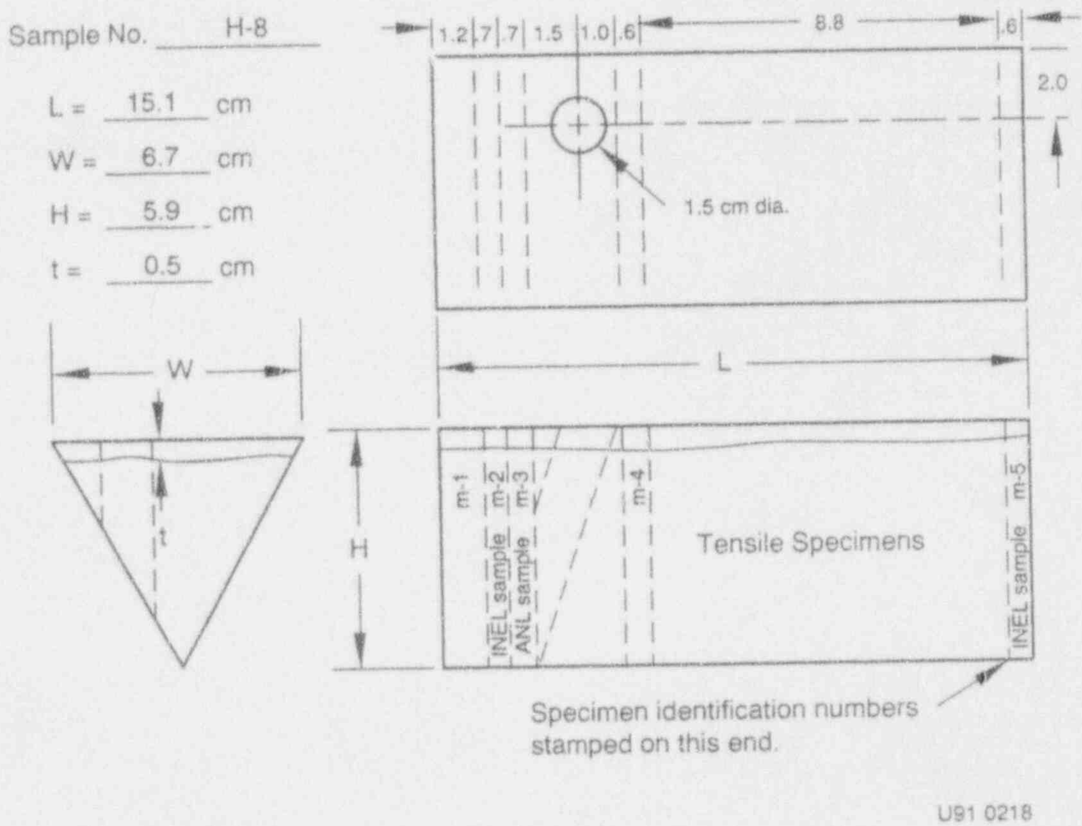
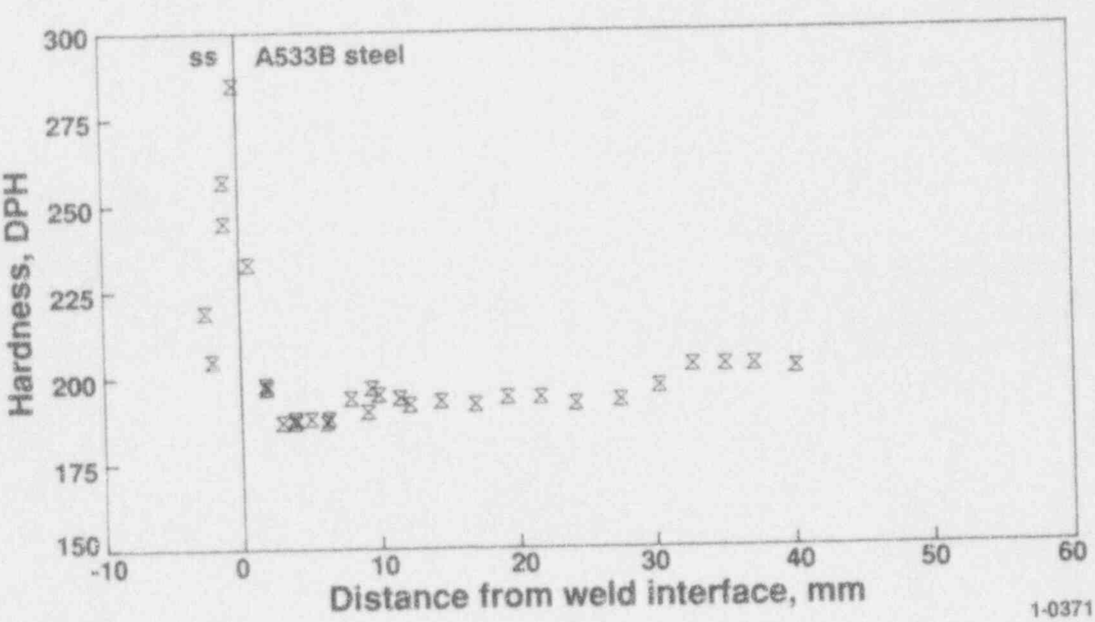
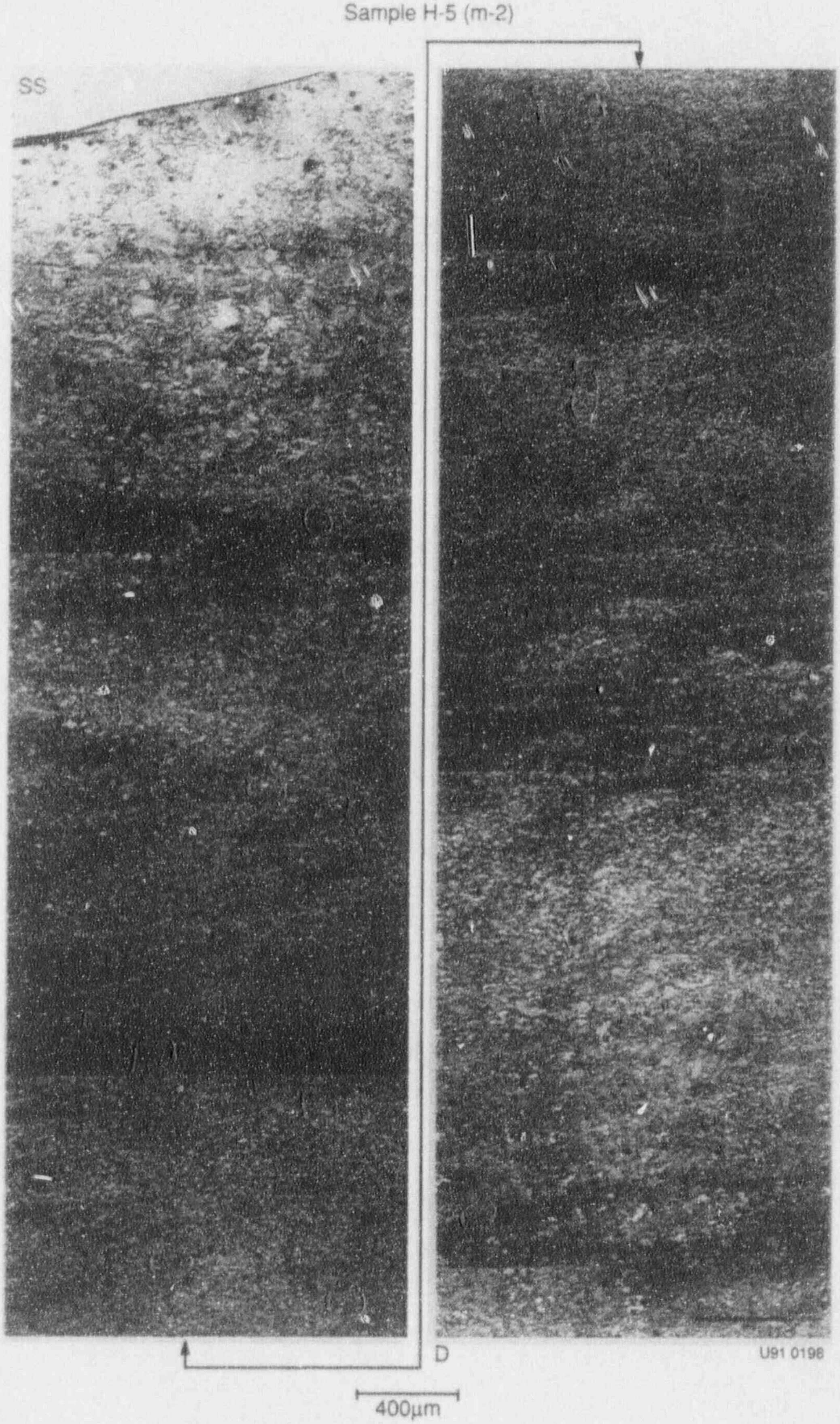
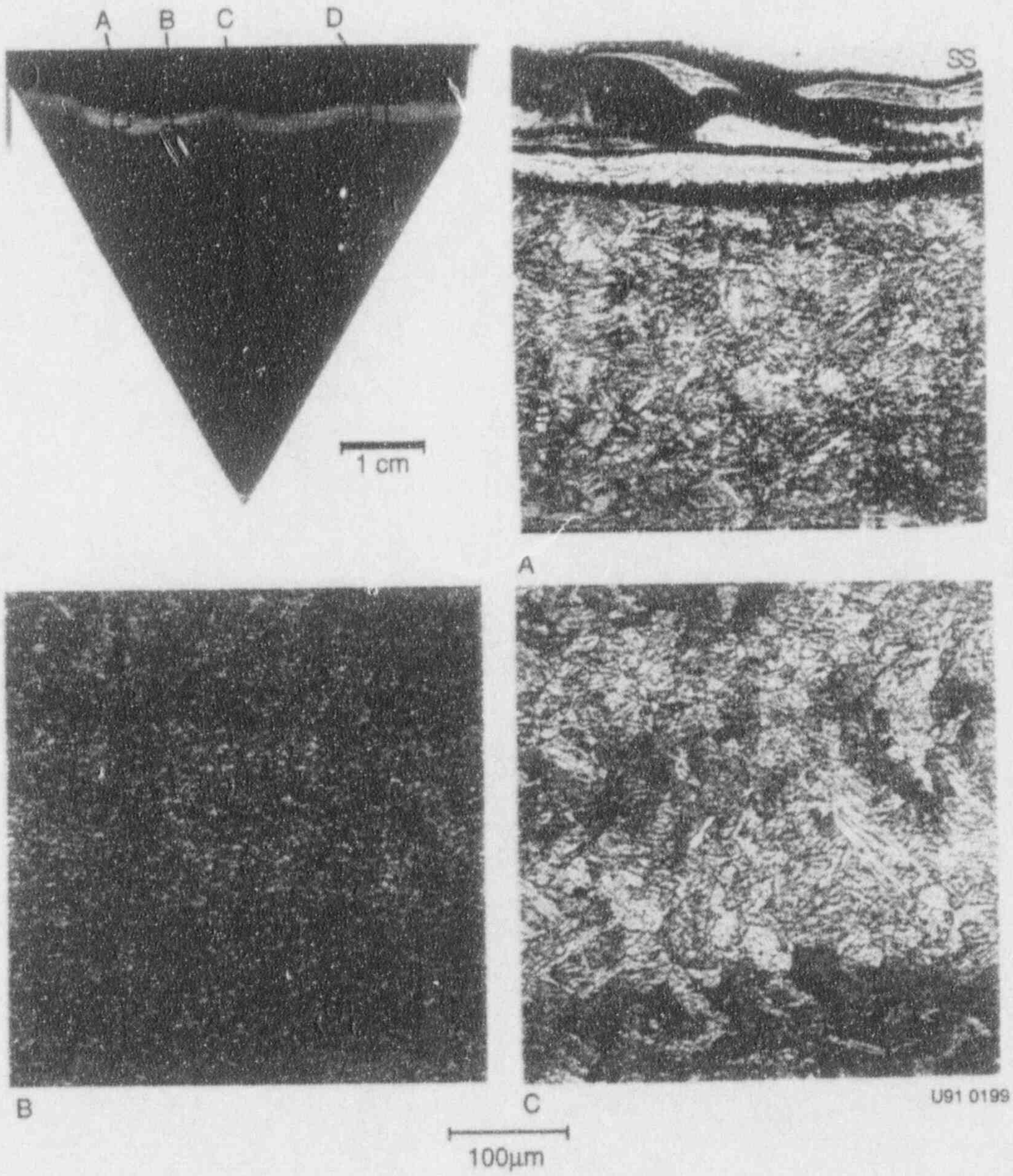
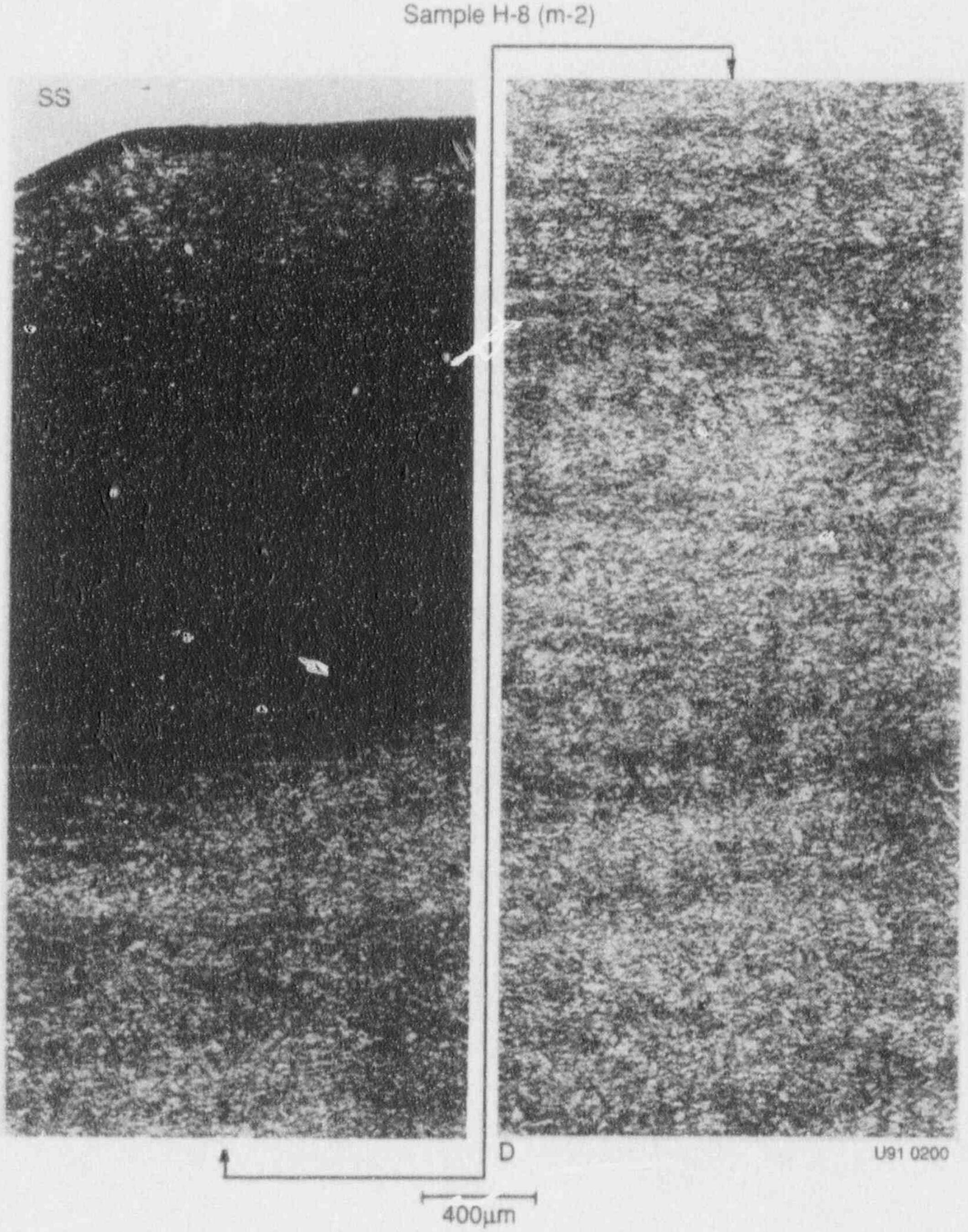




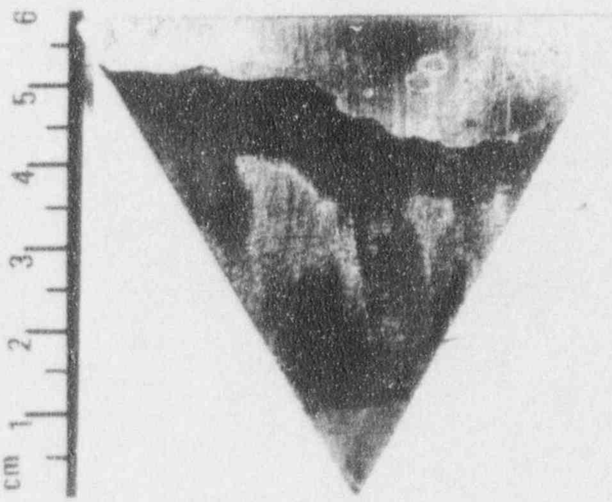

Sample H-5 (m-2)
SS
D
U91 0198
400μm

Sample H-8 (m-2)




Sample H-8 (m-2)
SS
D
U91 0200
400μm

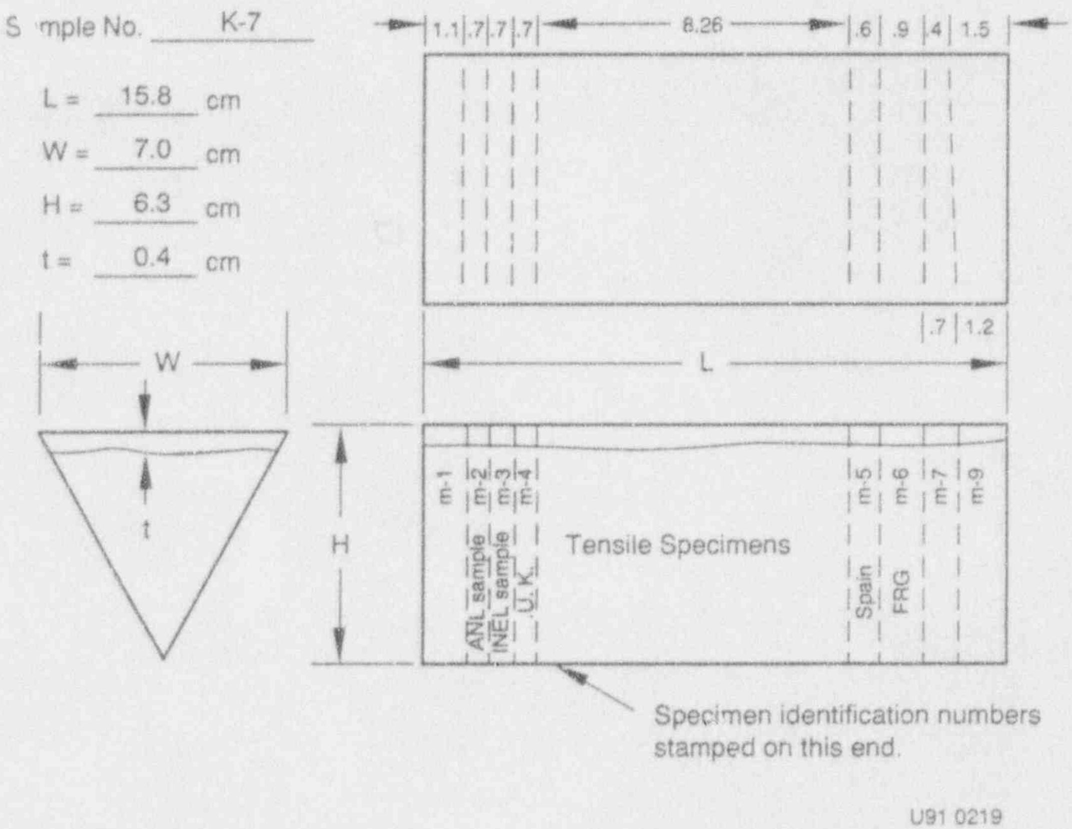
Sample H-8 (m-2)
(Backside)

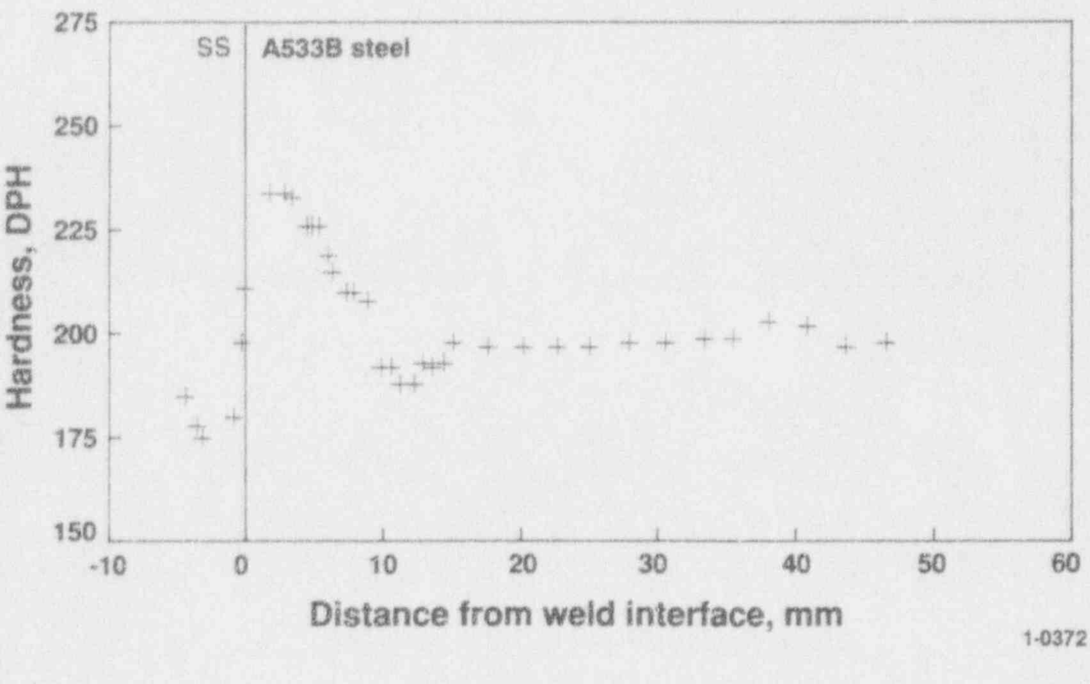


Near Nozzle Penetration

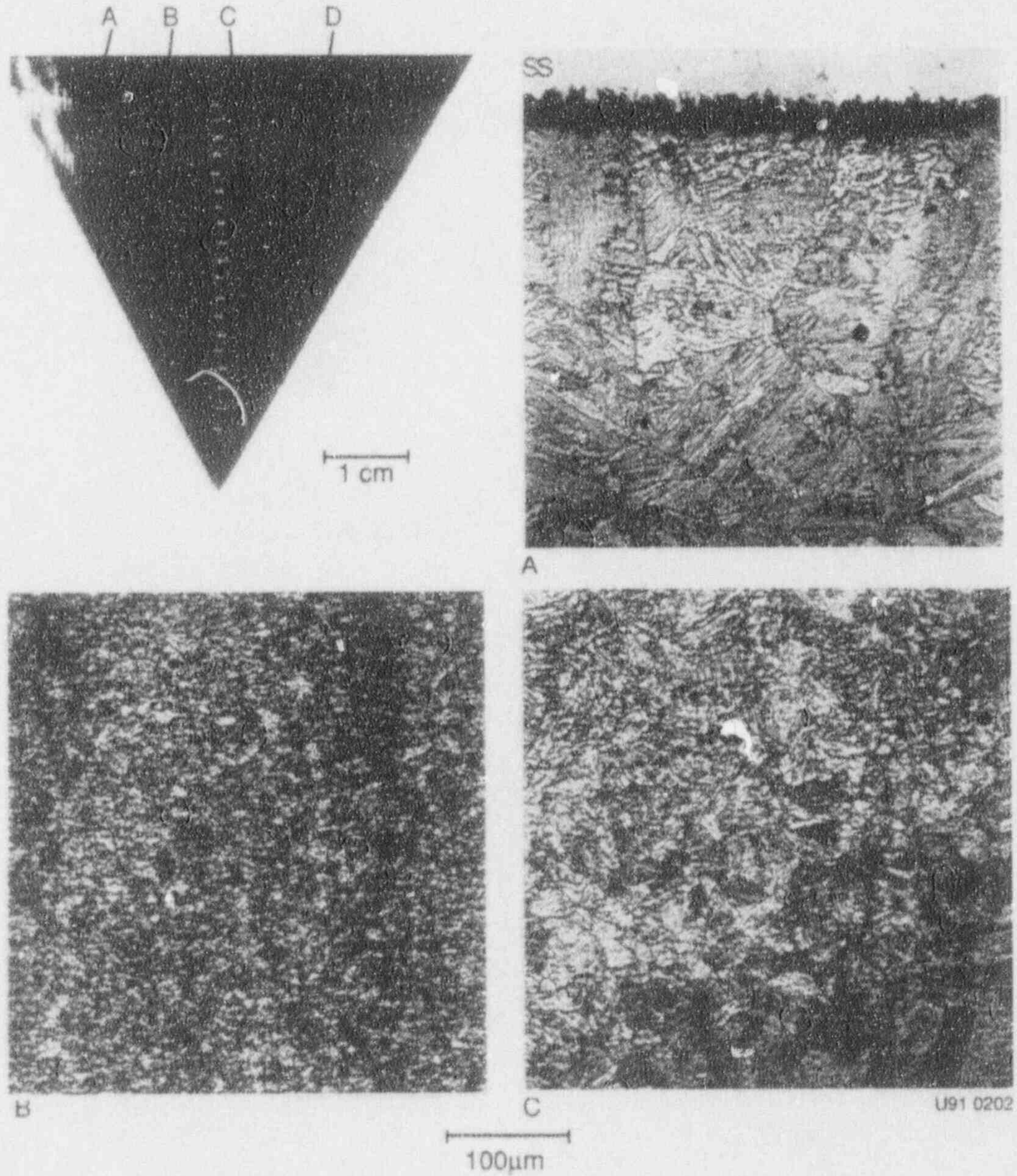
U91 0201

Sectioning diagram of TMI-2 lower head sample K-7 and hardness profile of INEL subsection K-7 (m-3)

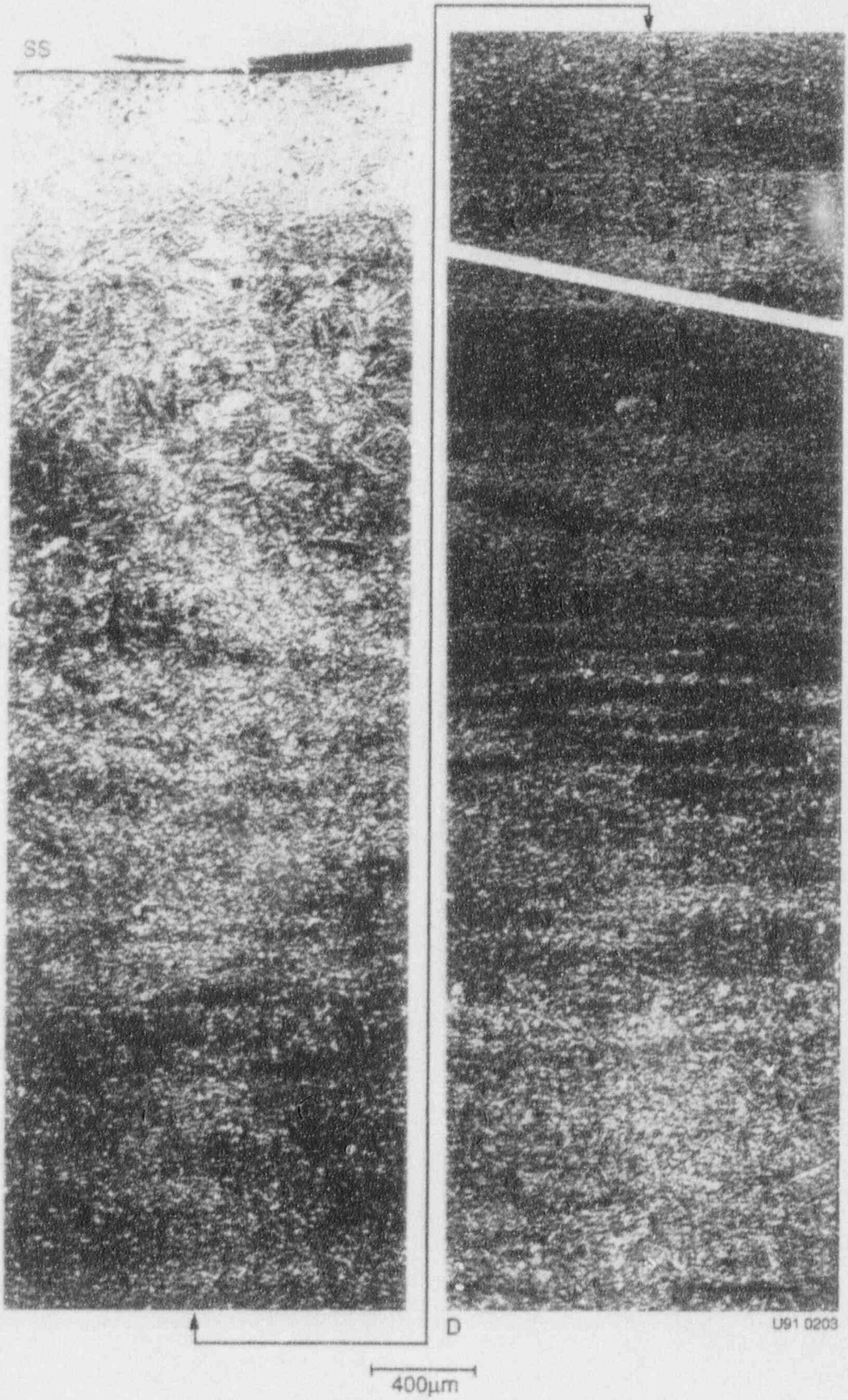




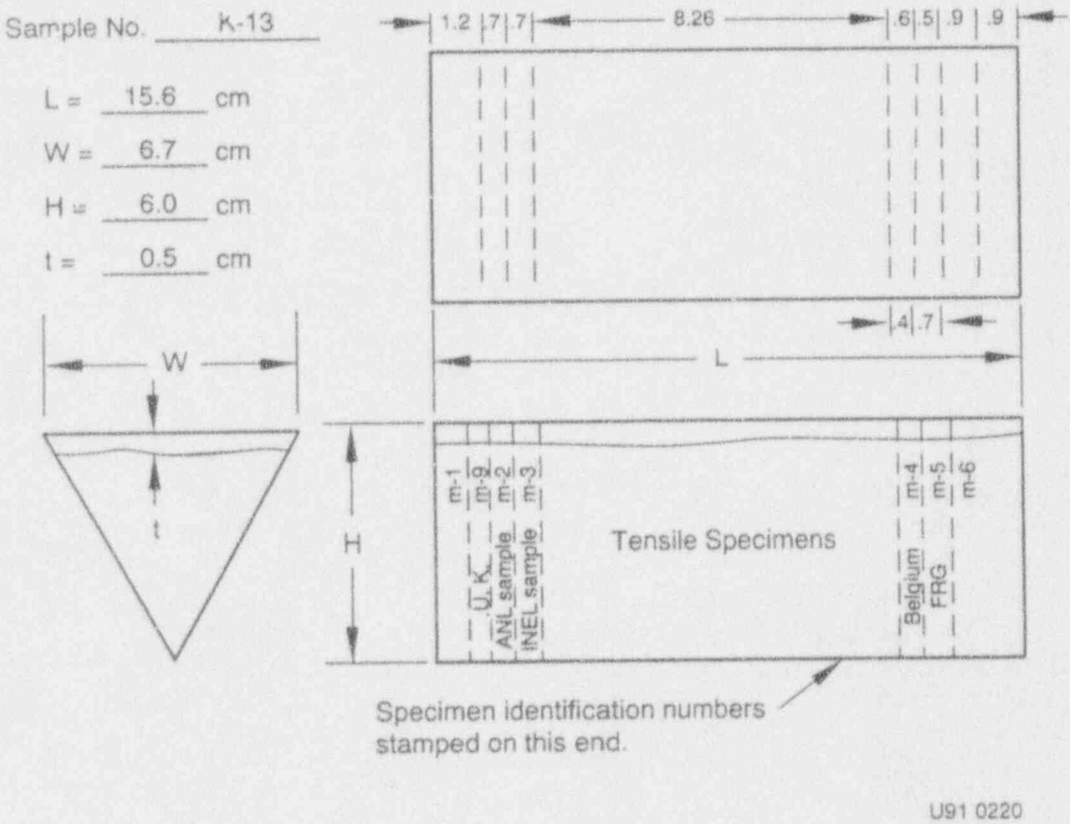
Sample K-7 (m-3)

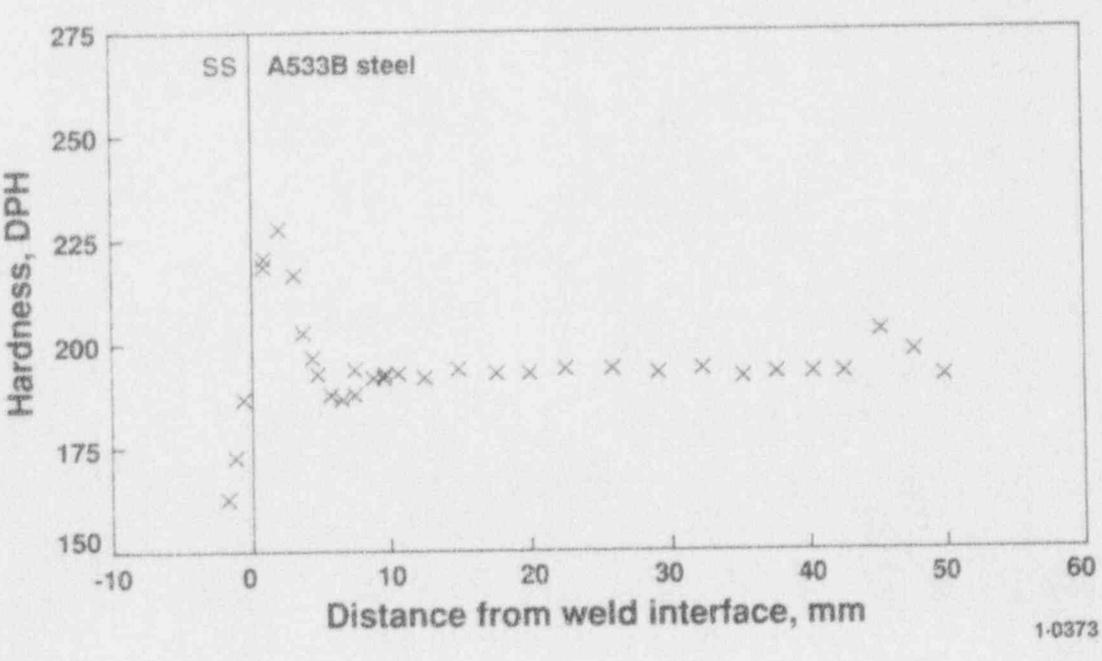


Sample K-7 (m-3)

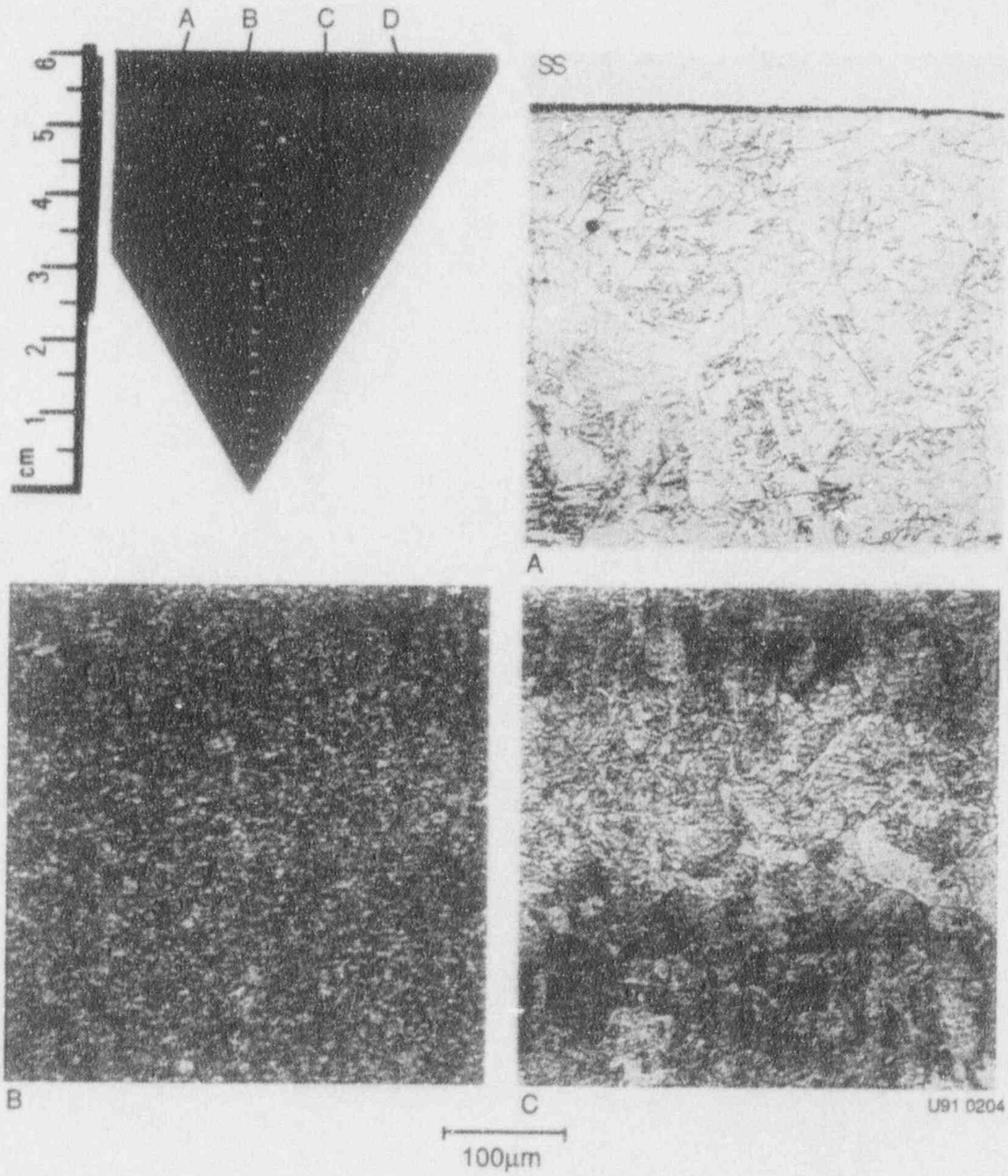


Sectioning diagram of TMI-2 lower head sample K-13 and hardness profile of INEL subsection K-13 (m-3)

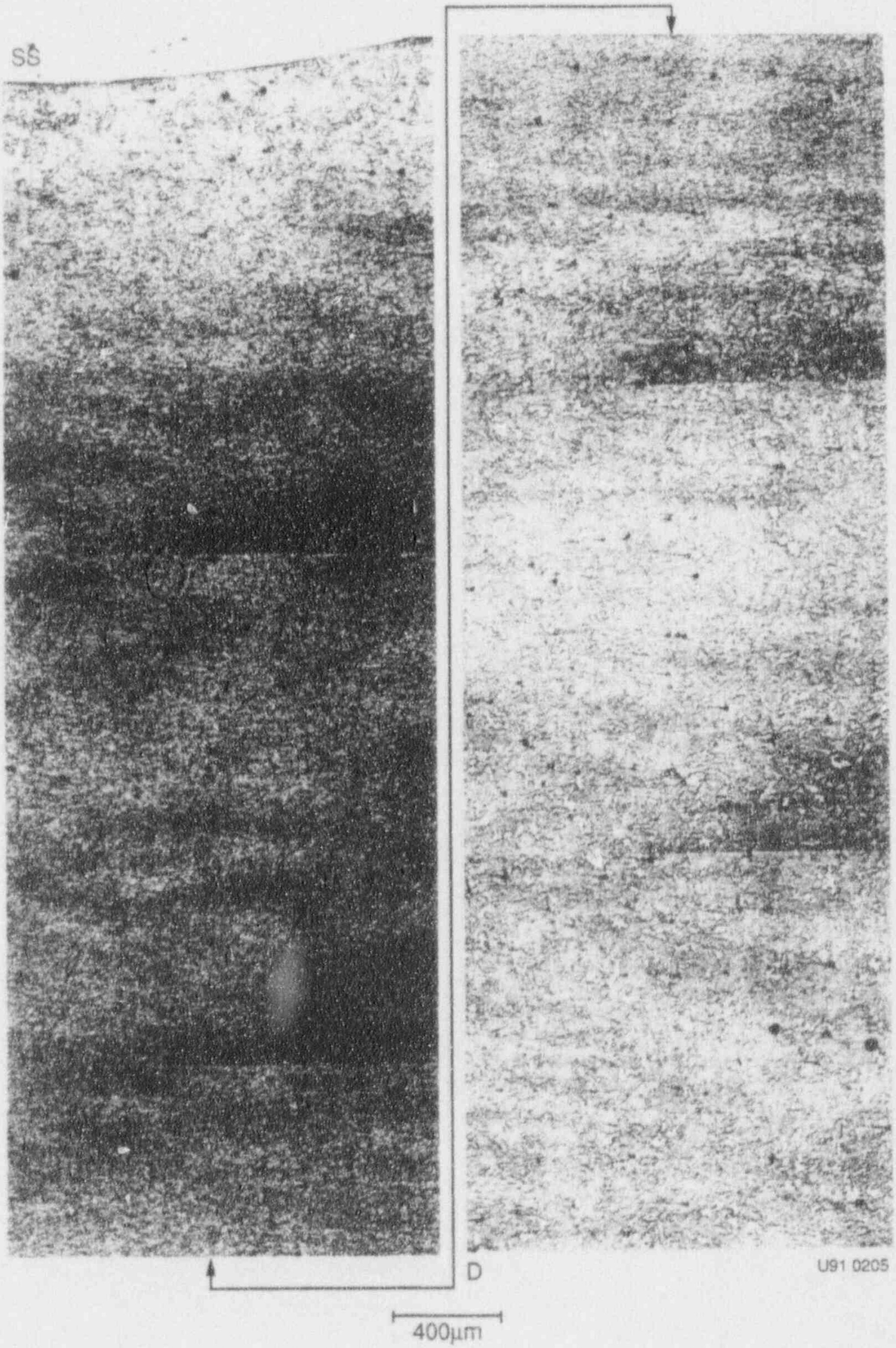




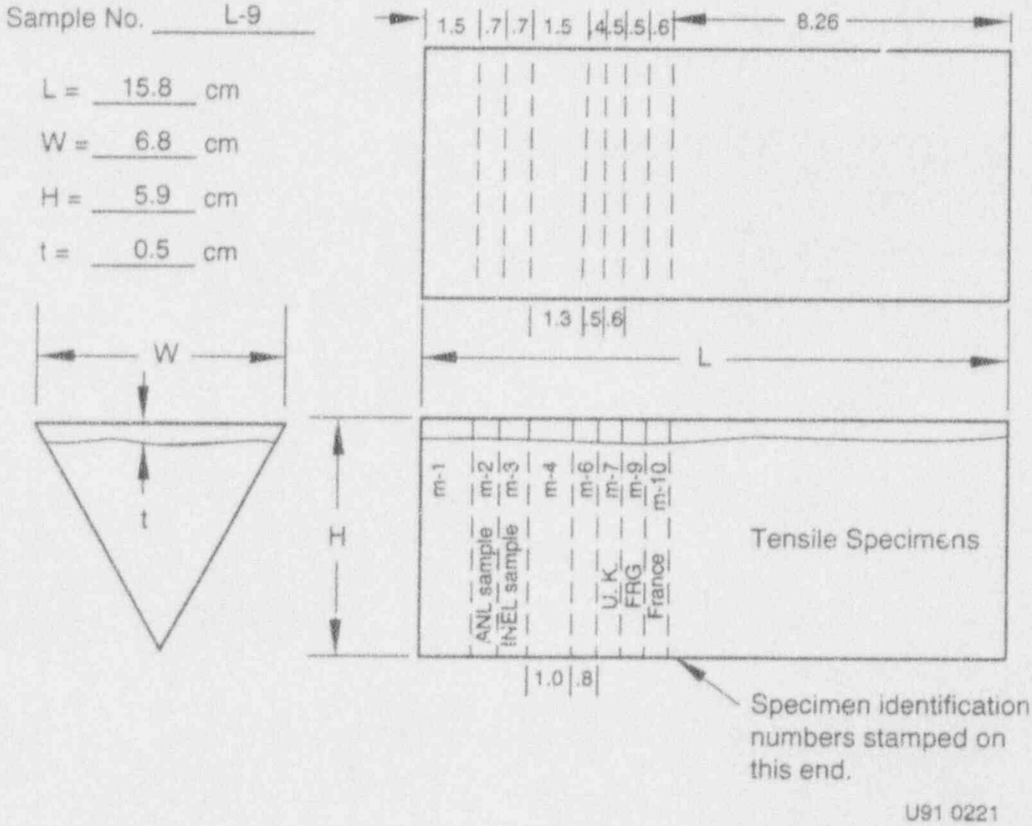
Sample K-13 (m-3)

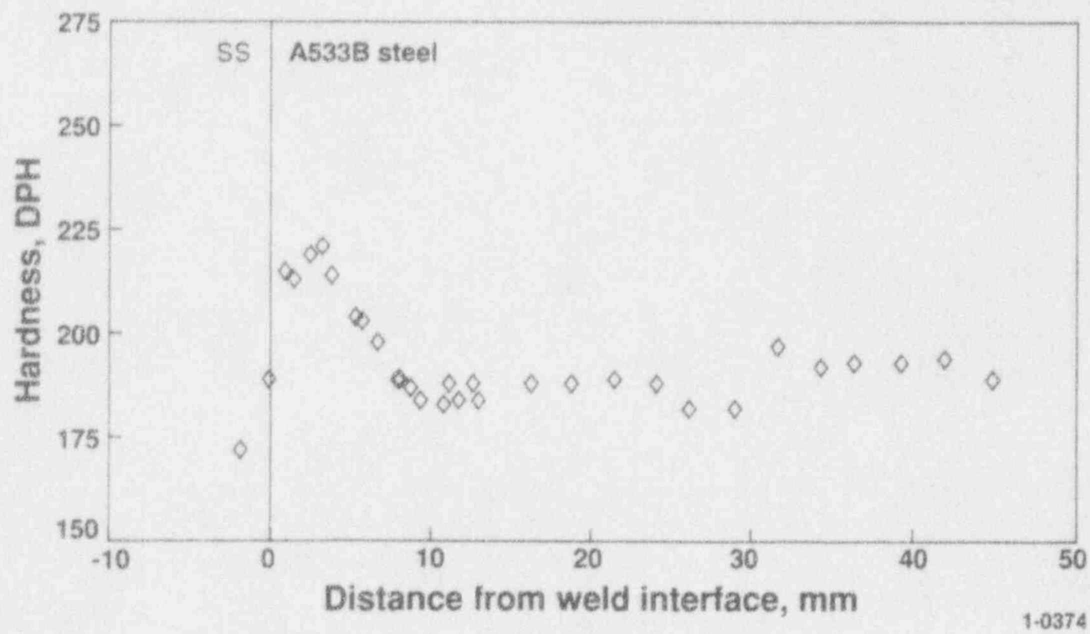


Sample K-13 (m-3)

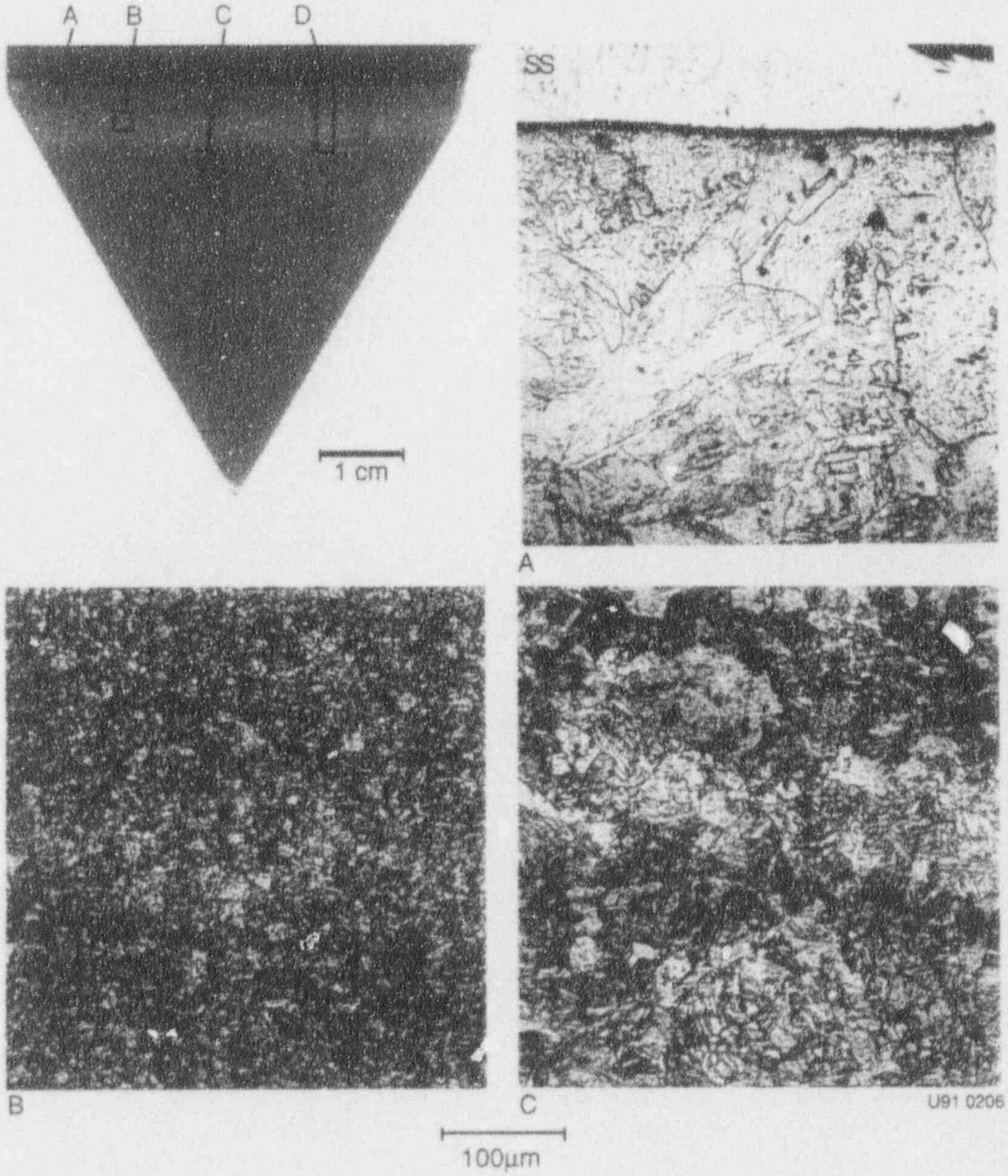


Sectioning diagram of TMI-2 lower head sample L-9 and hardness profile of INEL subsection L-9 (m-3)

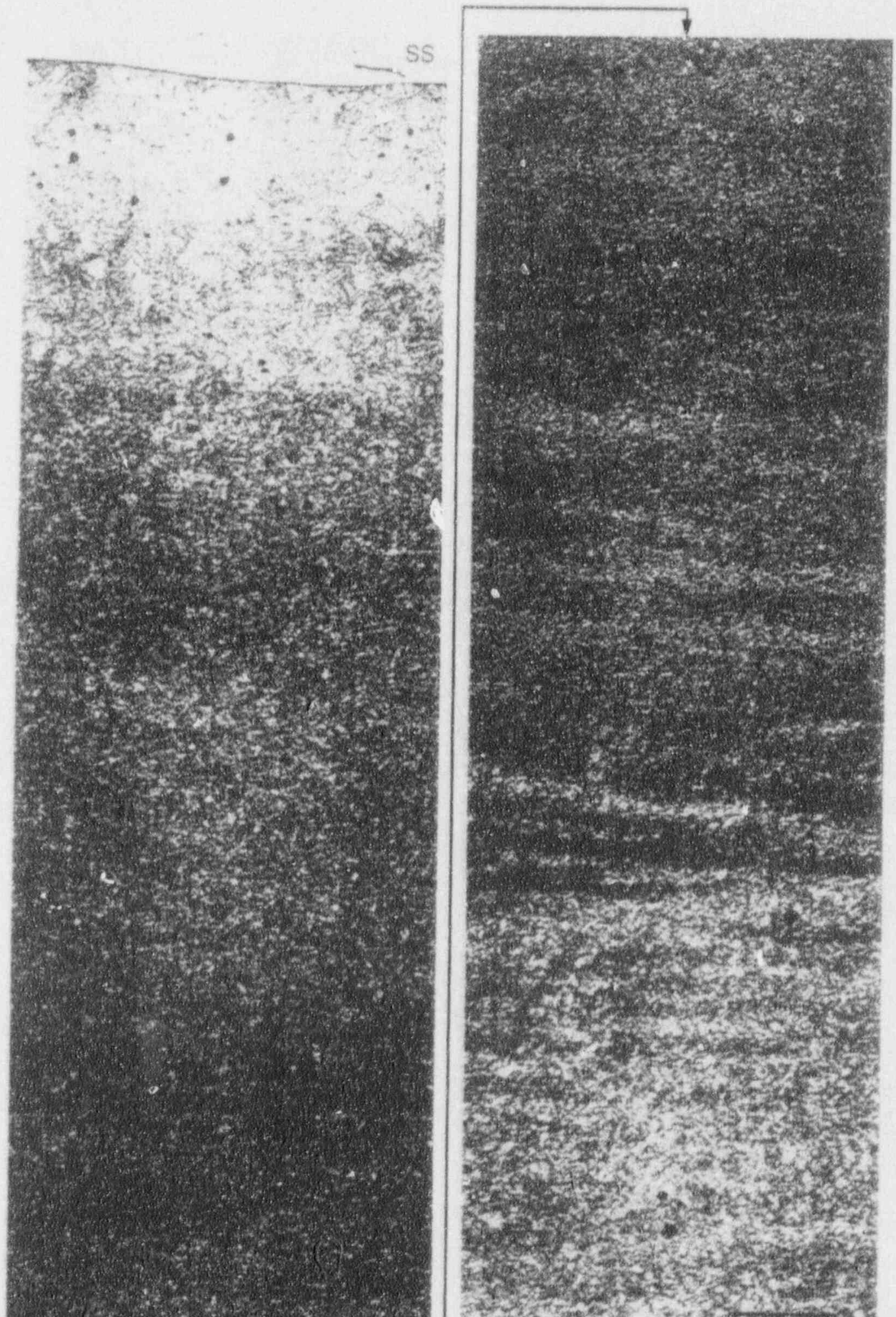




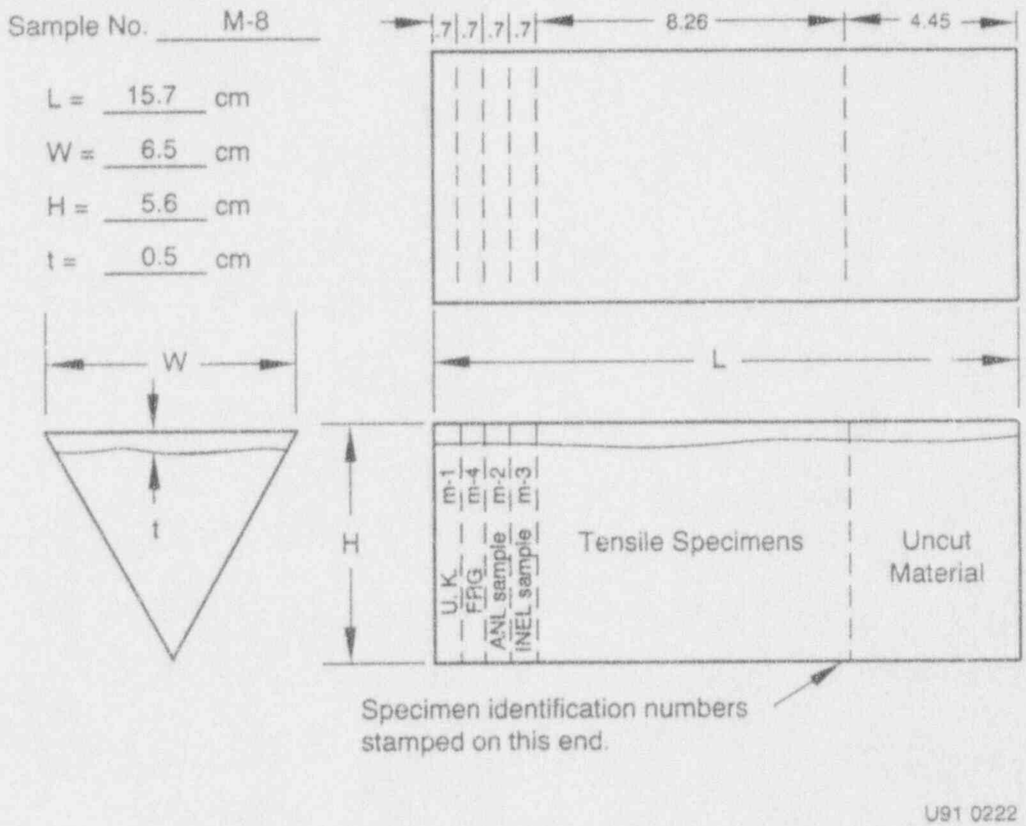
Sample L-9 (m-3)

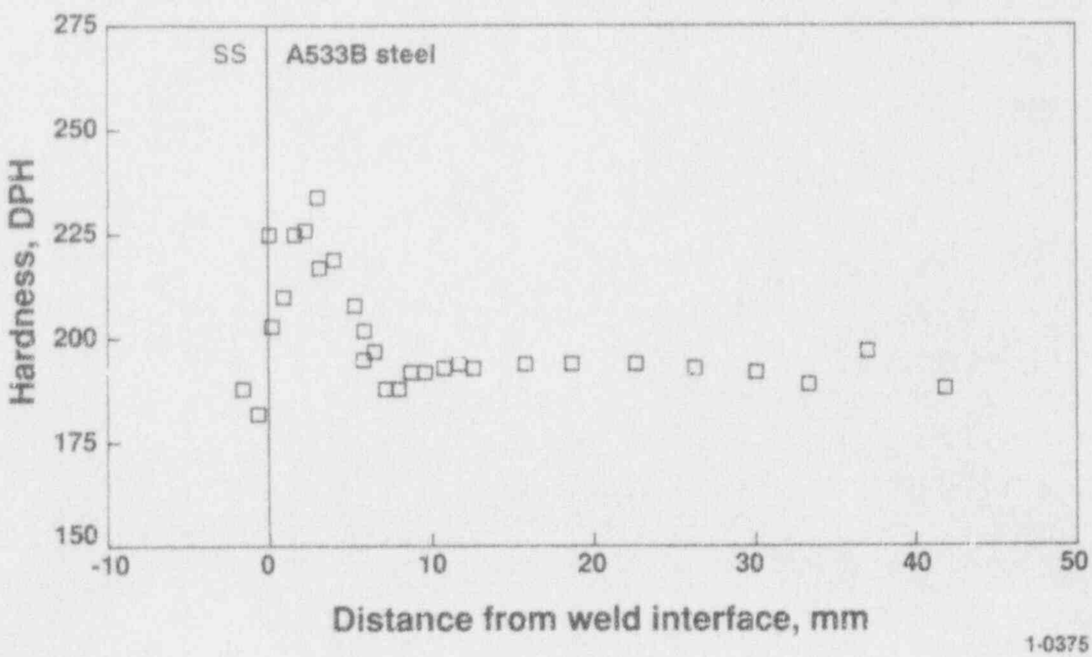


Sample L-9 (m-3)

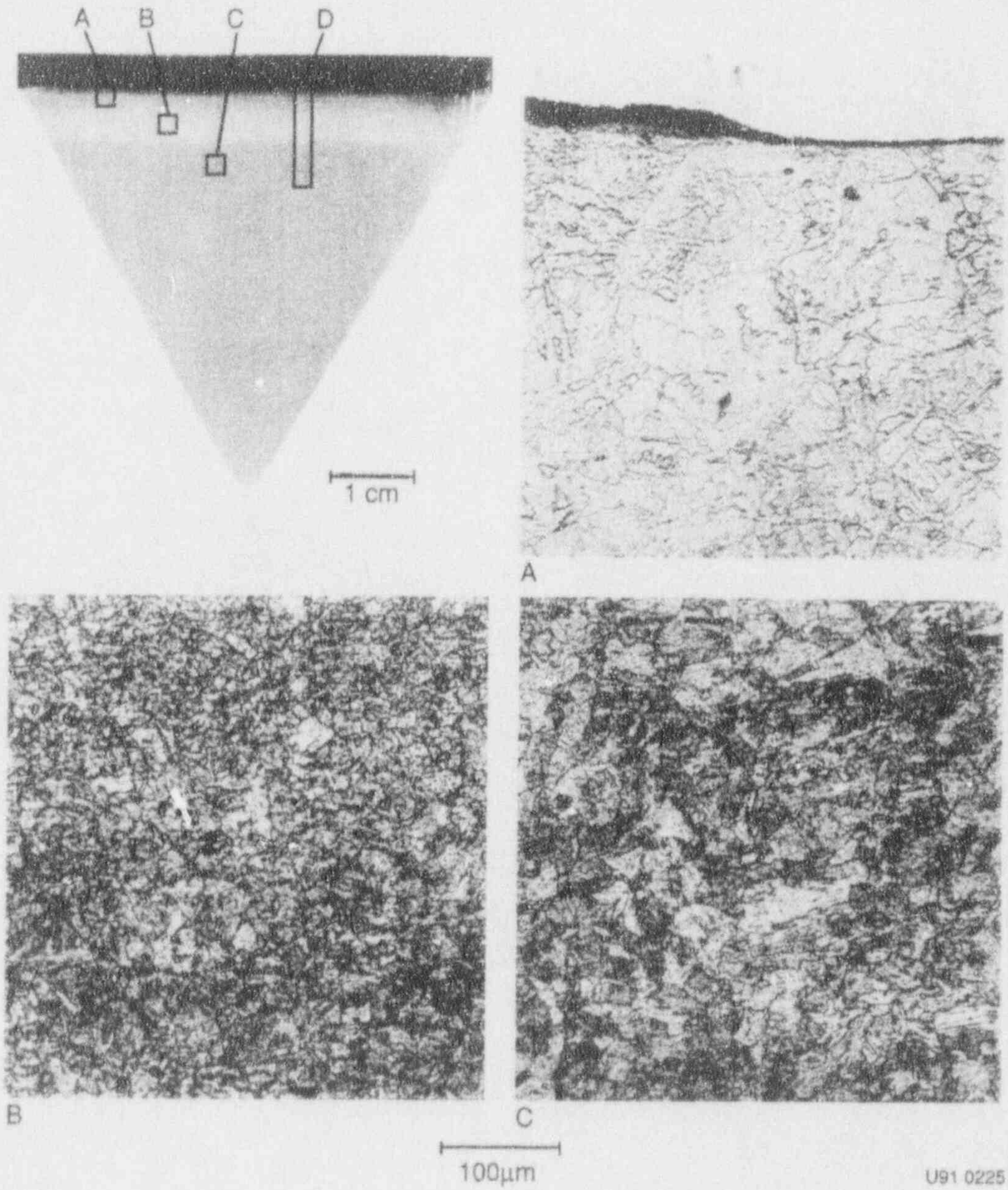


Sectioning diagram of TMI-2 lower head sample M-8 and hardness profile of INEL subsection M-8 (m-3)

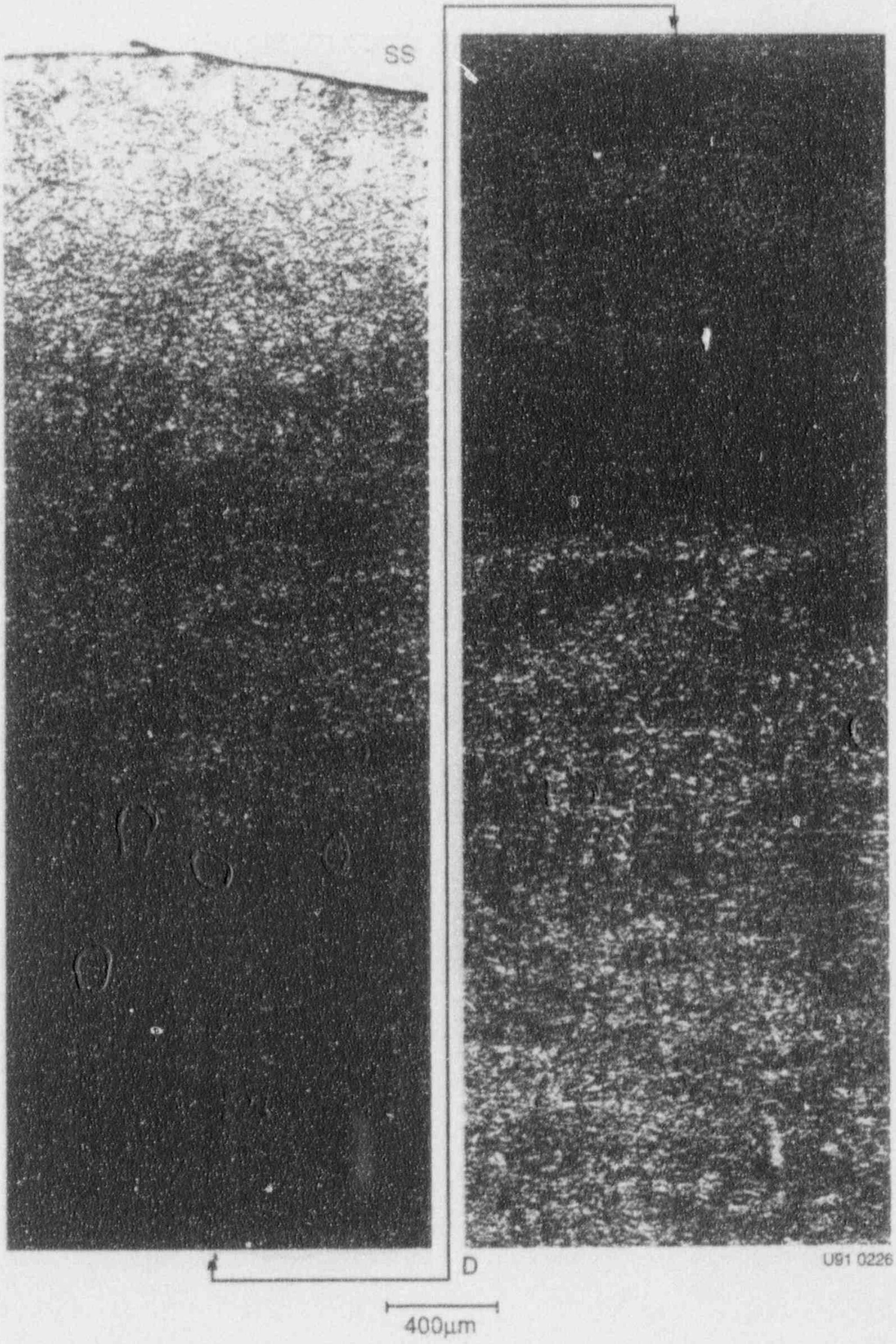




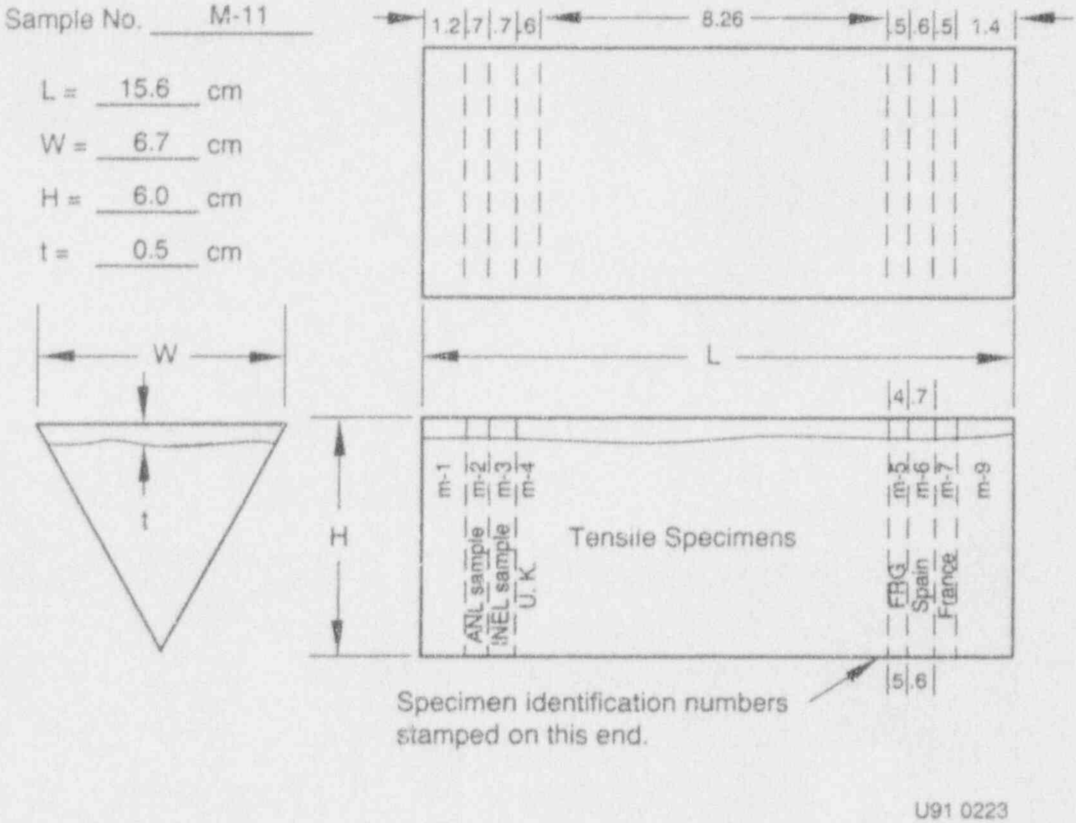
Sample M-8 (M-3)

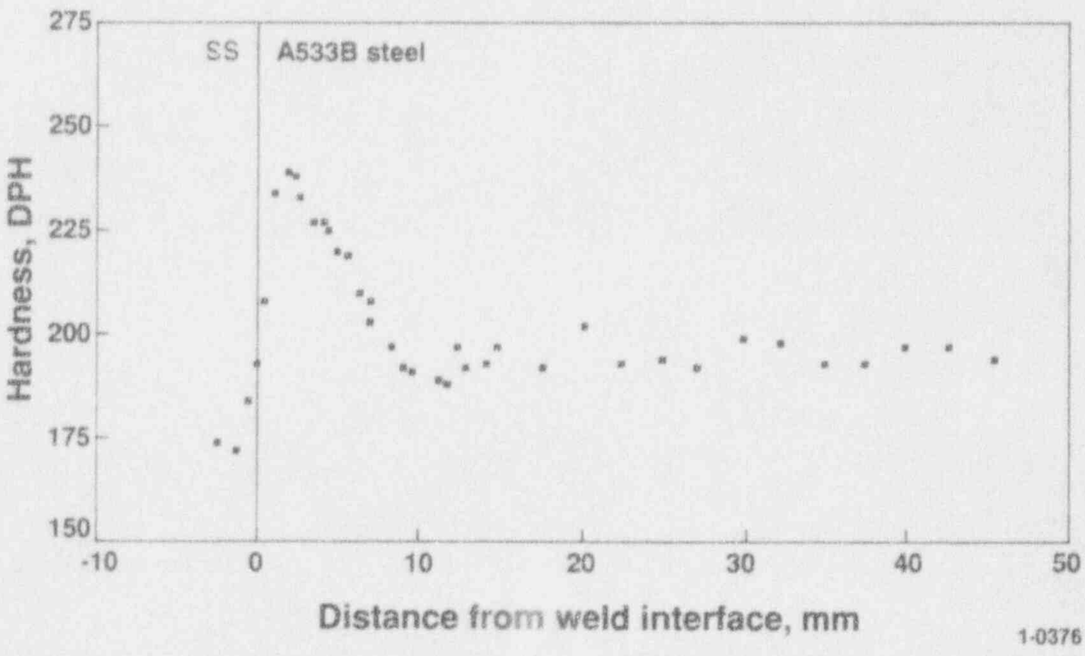


Sample M-8 (m-3)

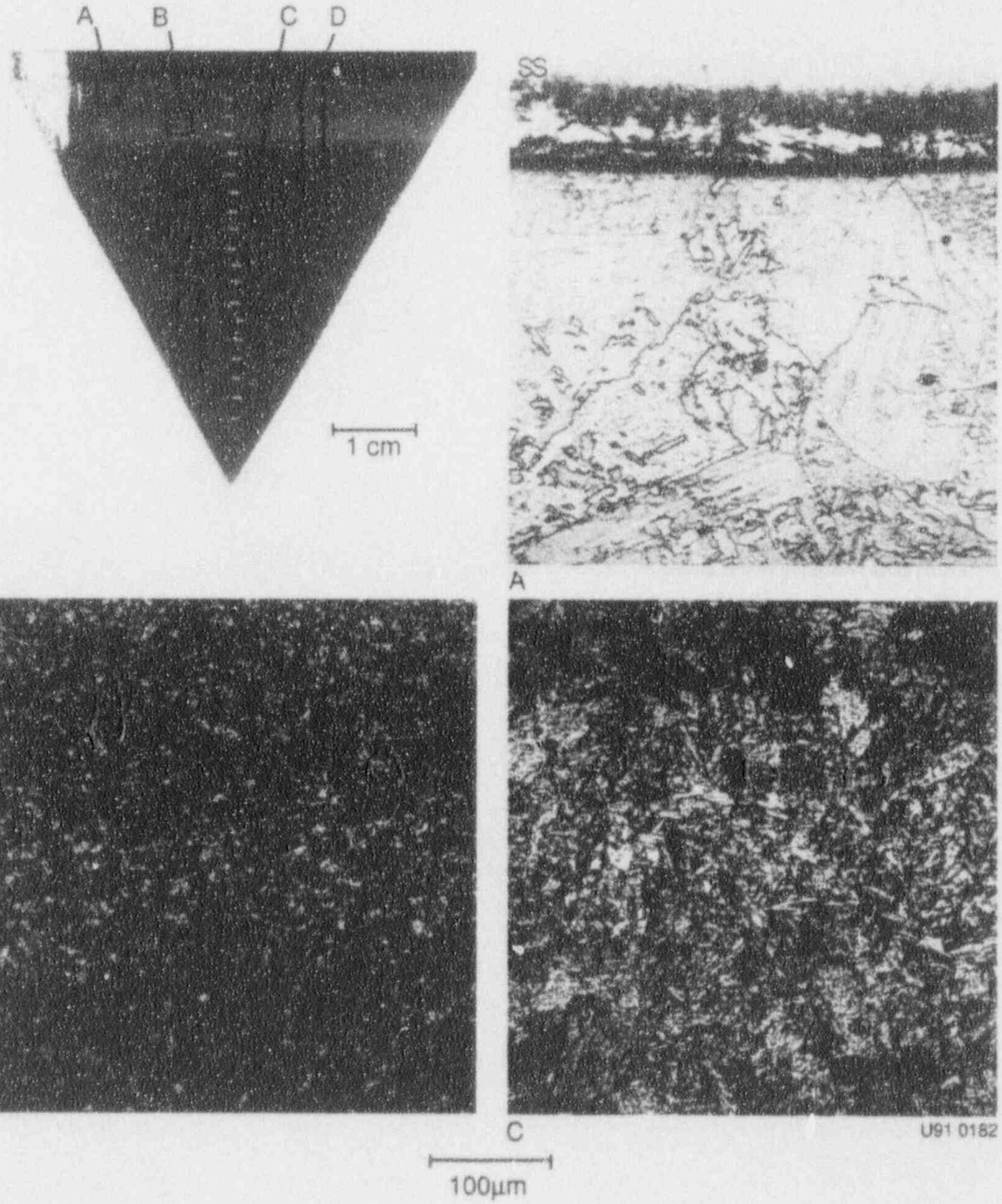


Sectioning diagram of TMI-2 lower head sample M-11 and hardness profile of INEL subsection M-11 (m-3)

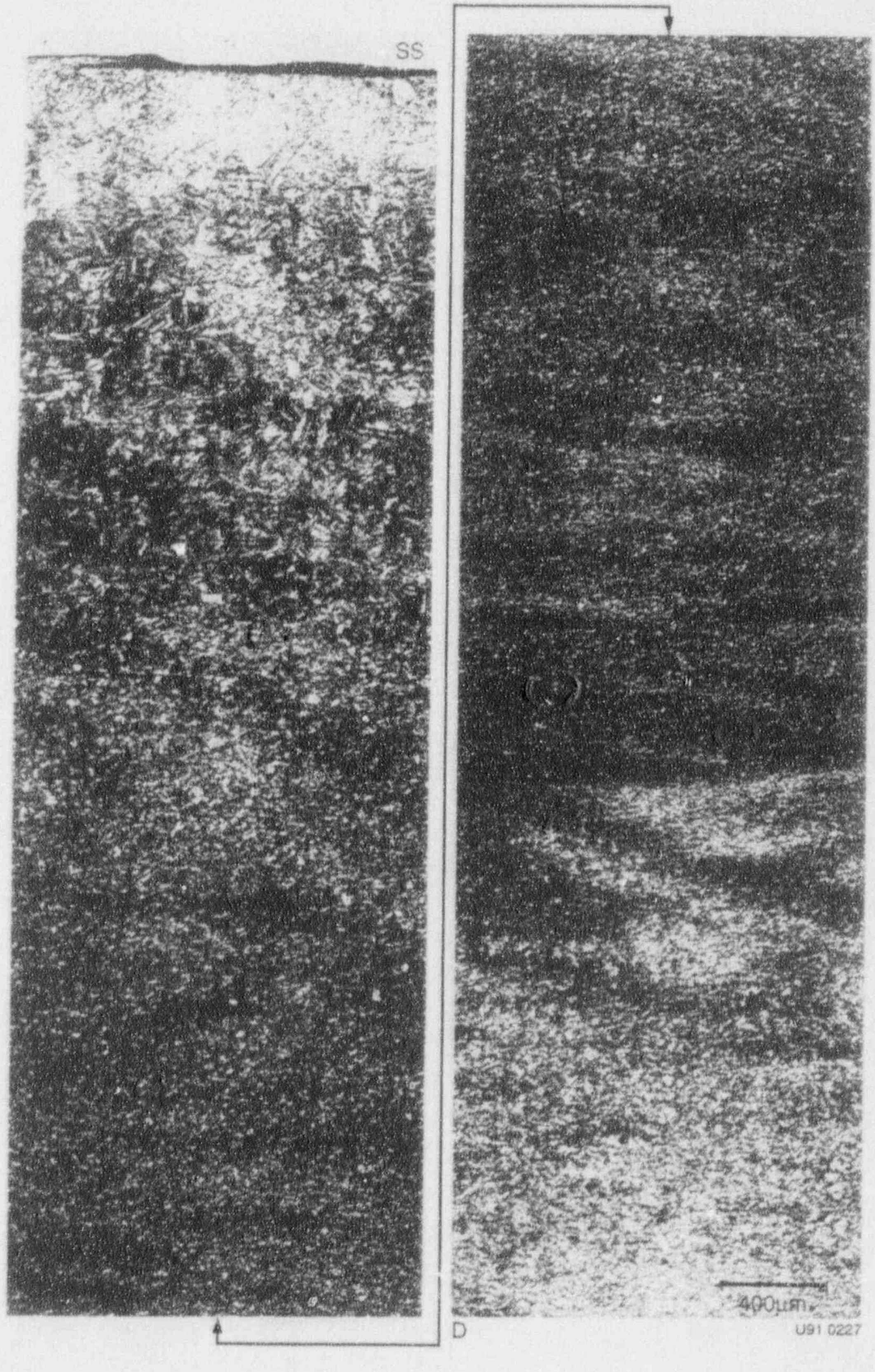




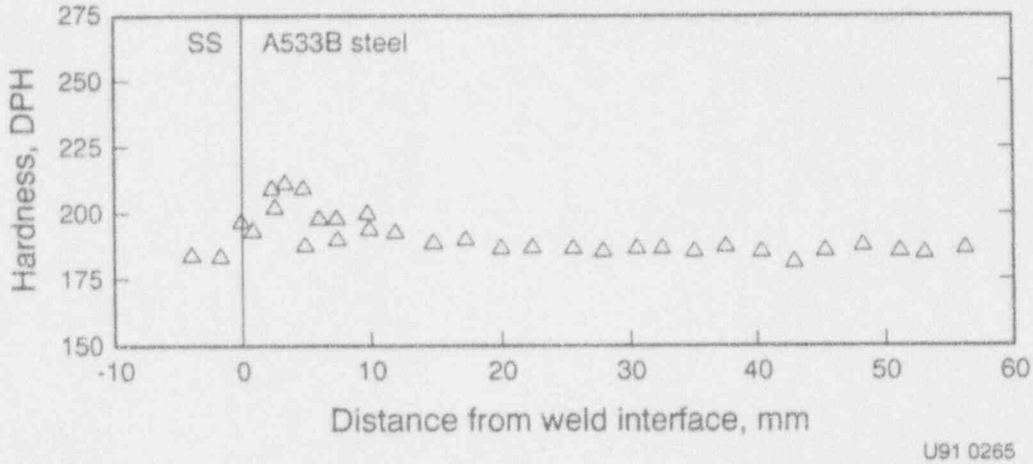
Sample M-11 (m-3)



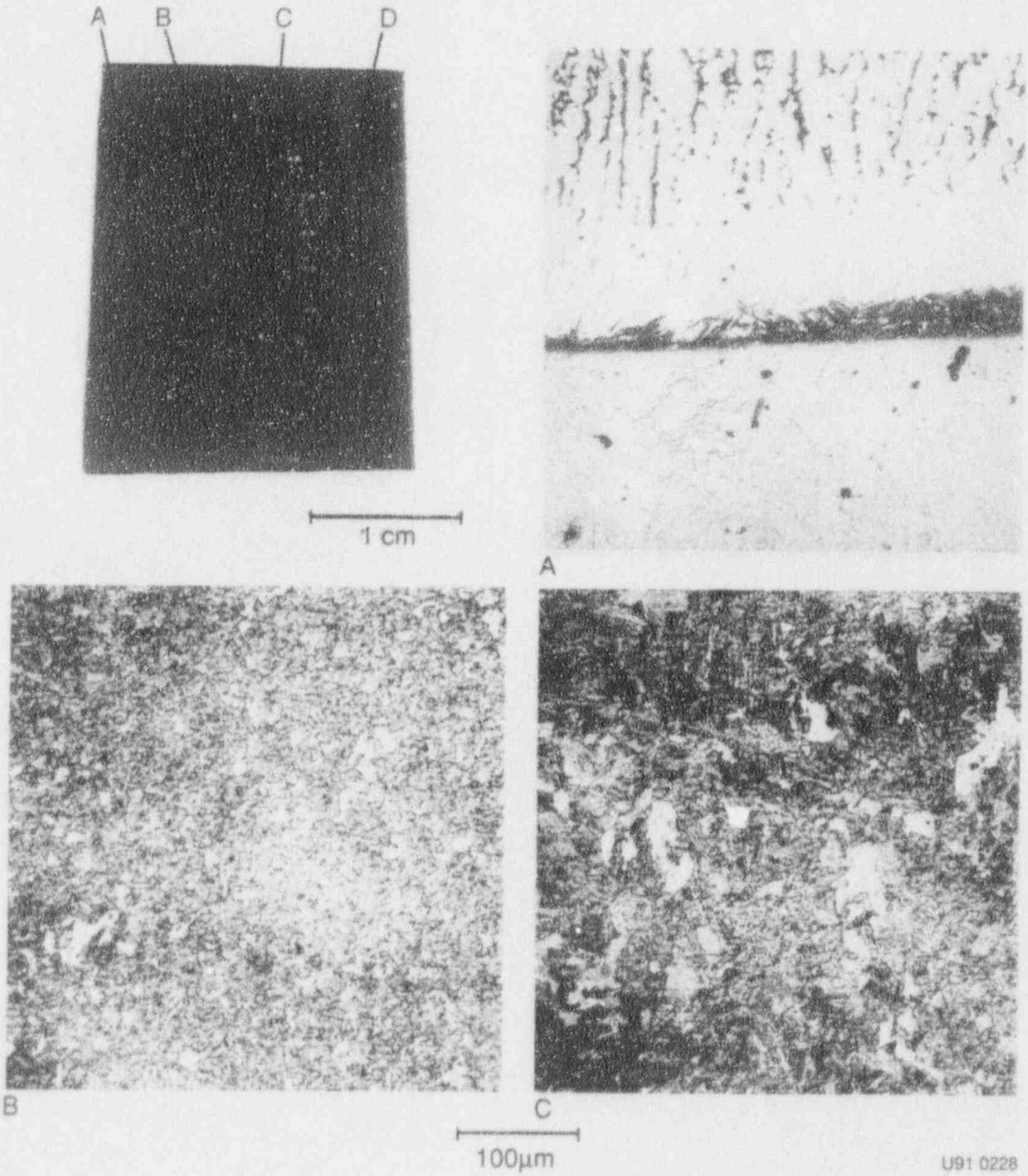
Sample M-11 (m-3)



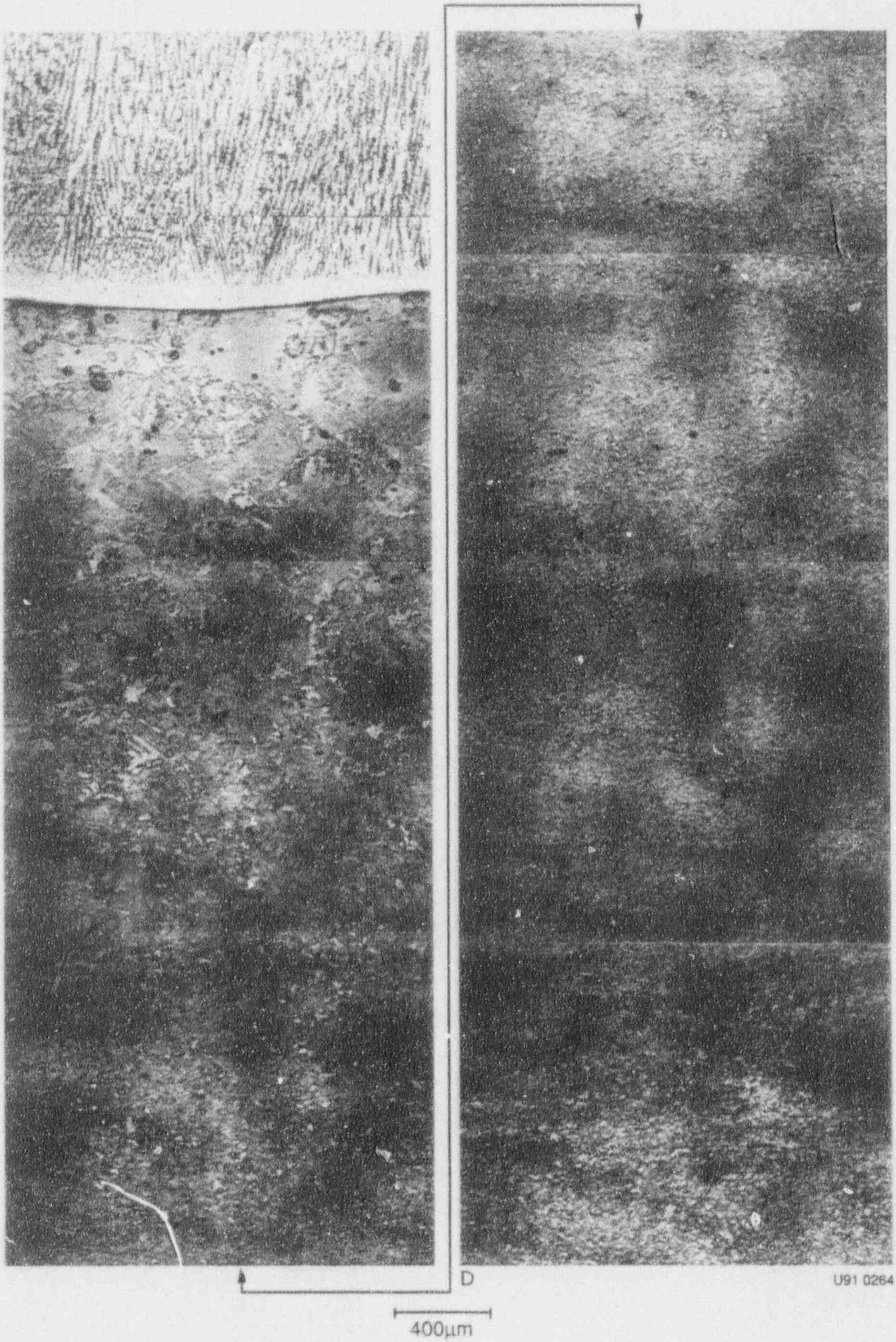
Hardness profile of Midland Archive material



Midland Archive Material

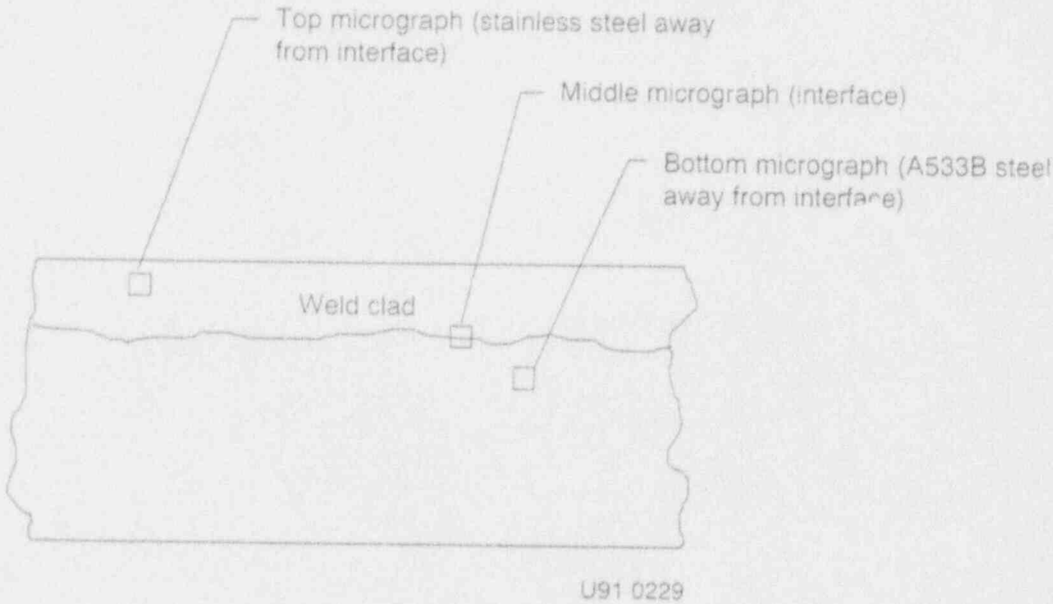


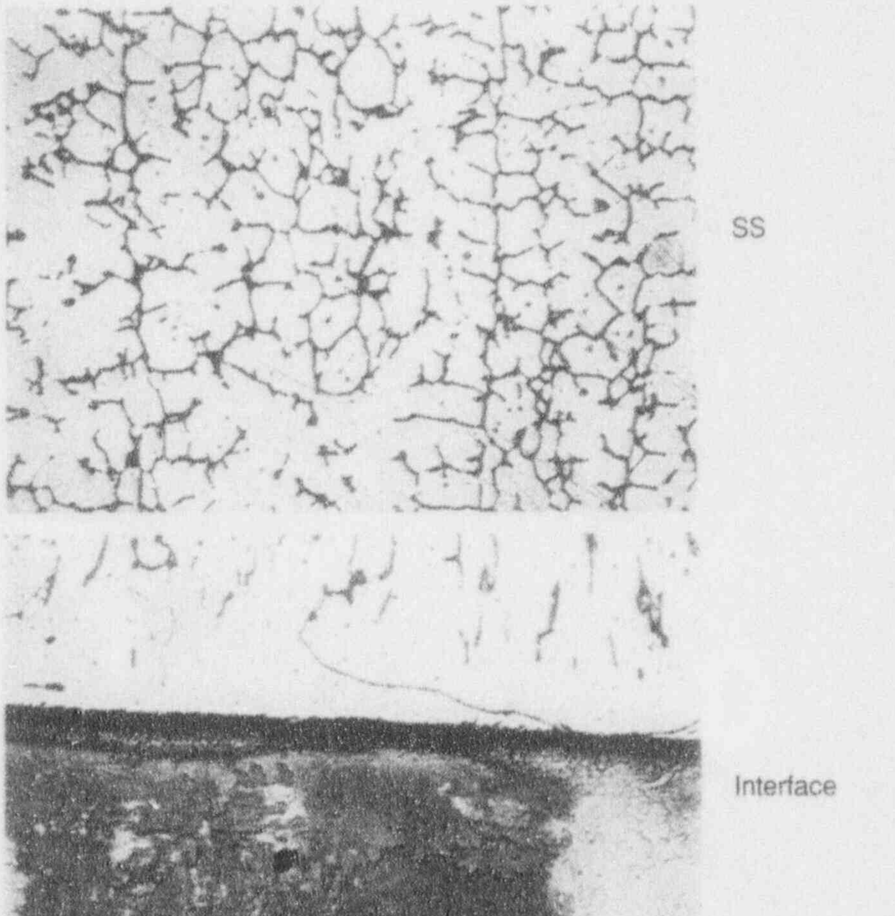
Midland Archive Material



Appendix B

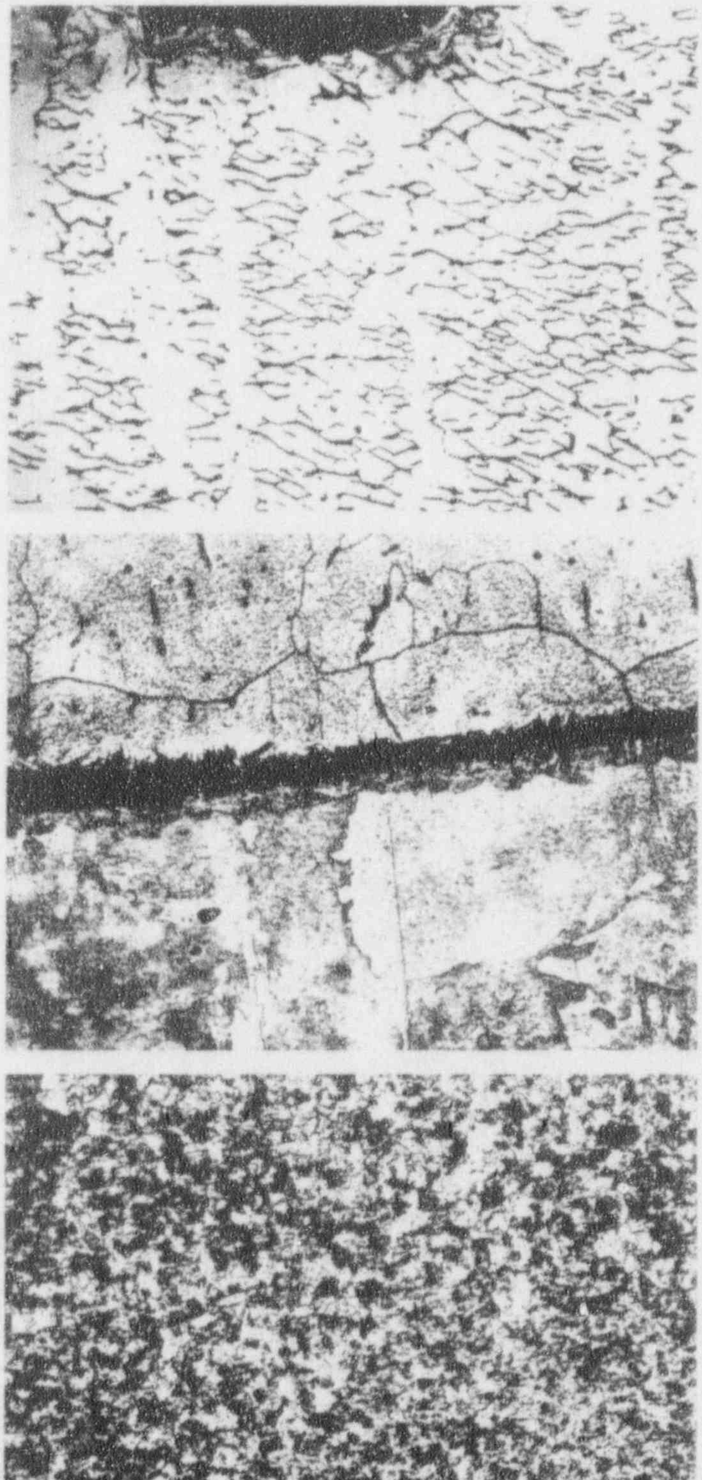
Microstructure of First Series of Midland Archive Samples Given Accident-Simulated Heat Treatments


Top micrograph (stainless steel away from interface)
Middle micrograph (interface)
Bottom micrograph (A533B steel away from interface)
Weld clad
U91 0229



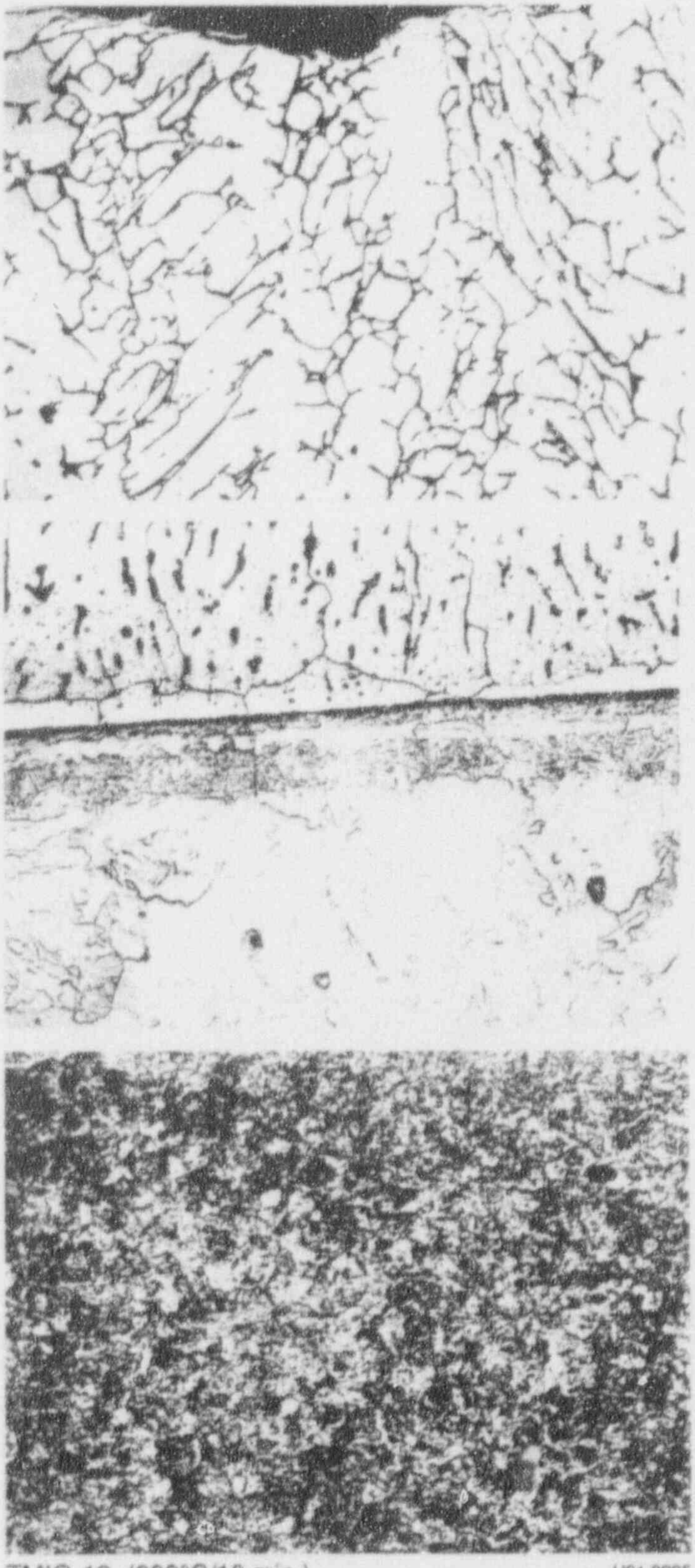
Midland archive material (as fabricated) U91 0230

50μm



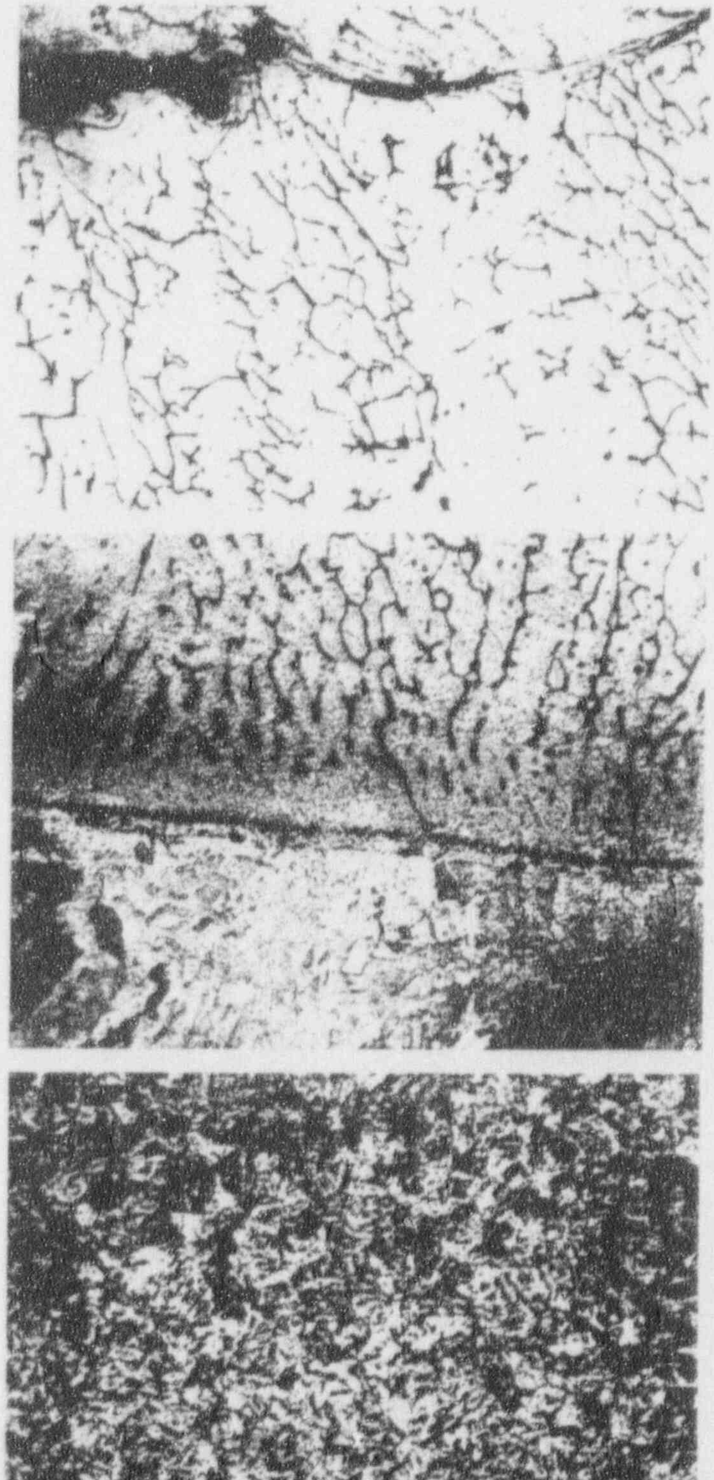
TMIG-15 (800°C/1 min.) U91 0231

50μm



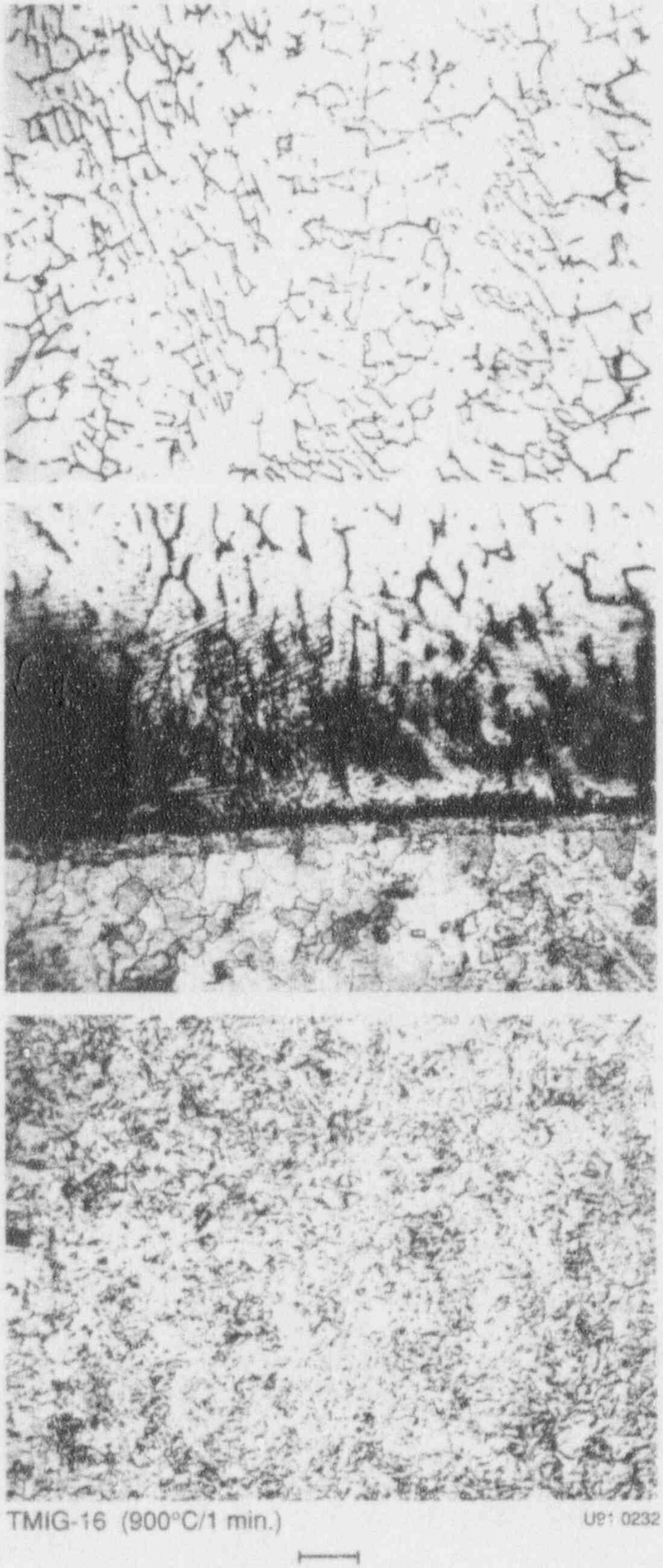
TMIG-19 (800°C/10 min.) U91 0235

50μm



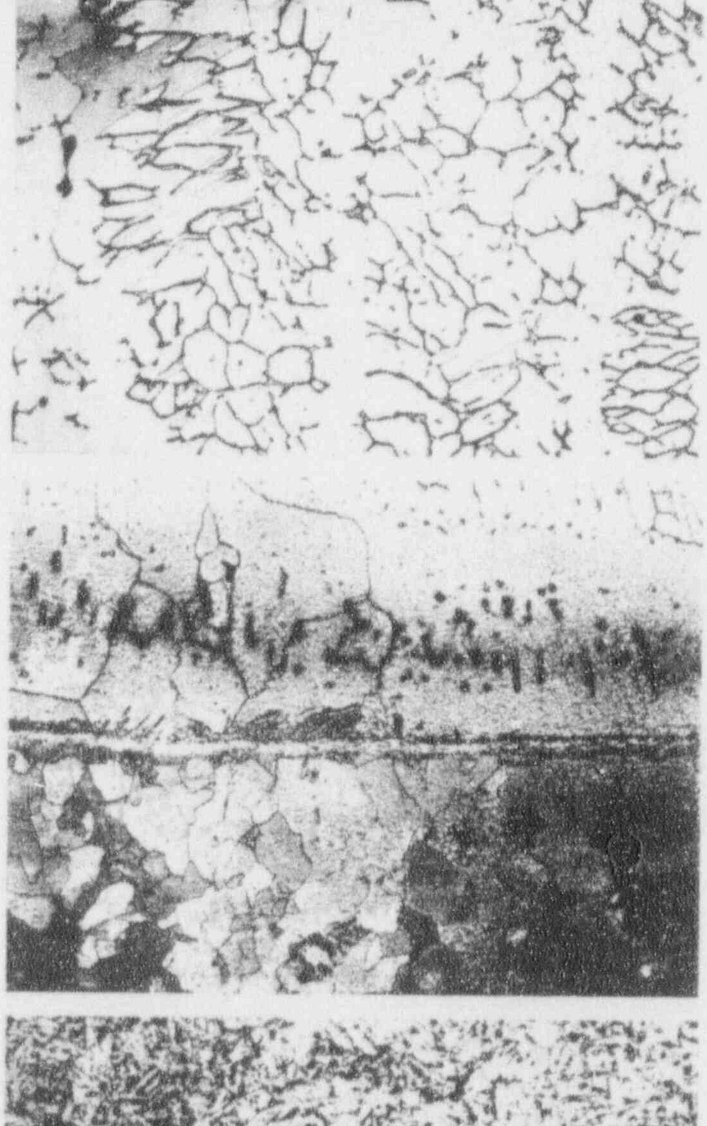
TMIG-23 (800°C/100 min.) U91 0239

50μm



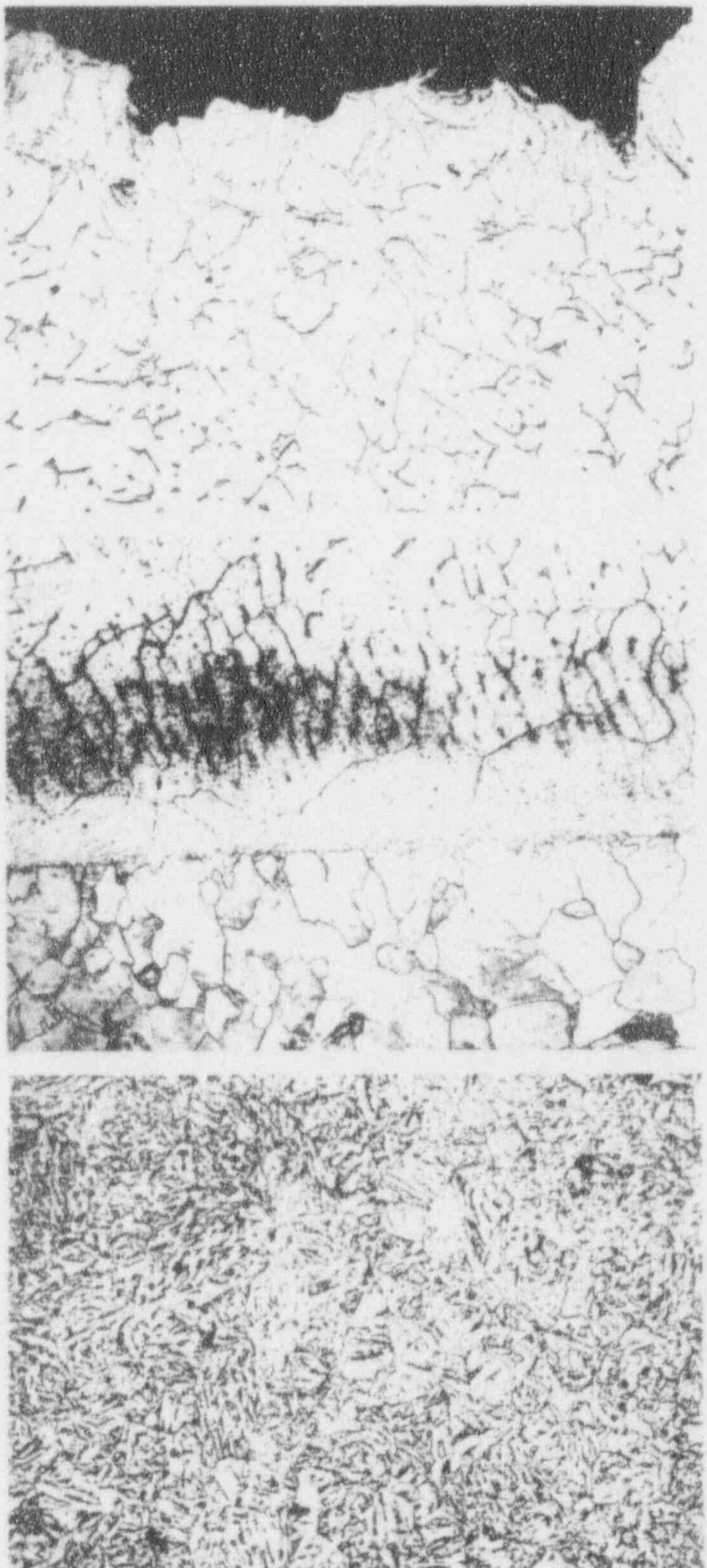
TMIG-16 (900°C/1 min.) U91 0232

50μm



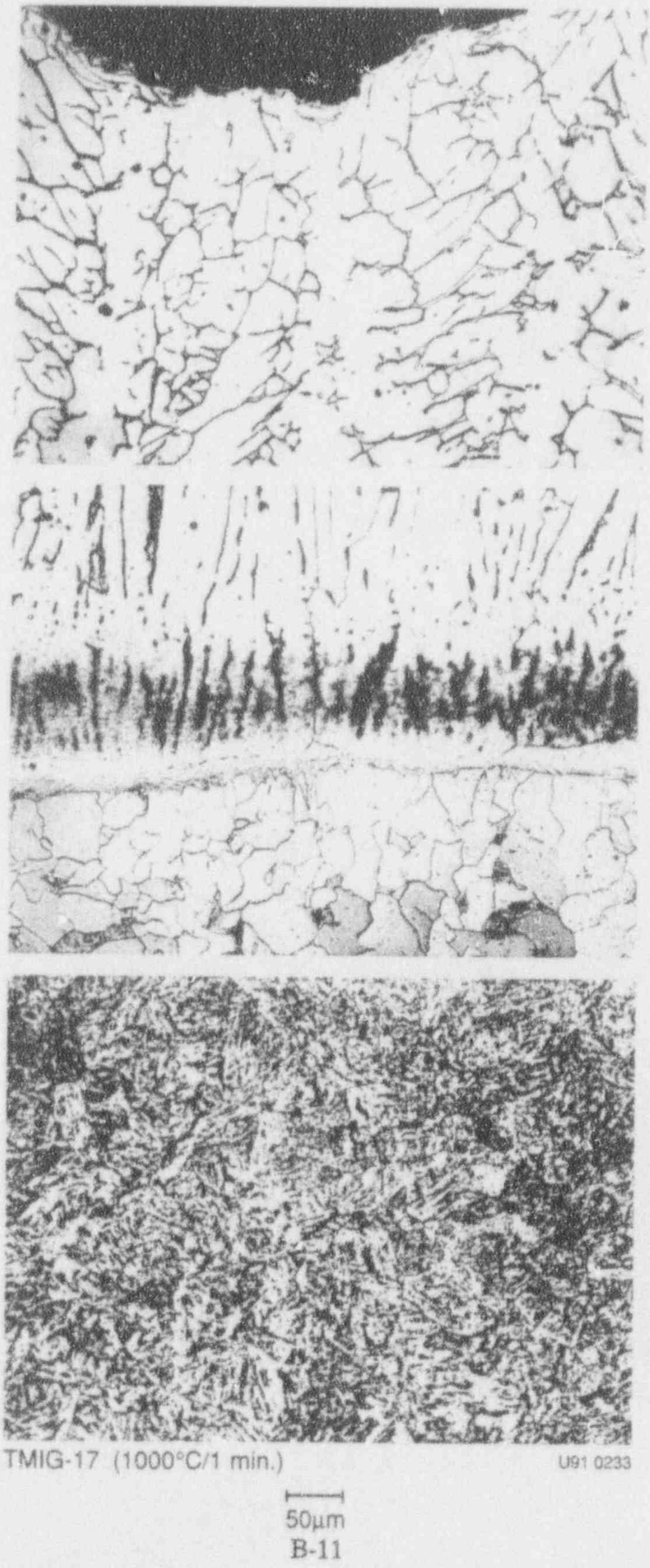
TMIG-20 (900°C/10 min.) U91 0236

50μm

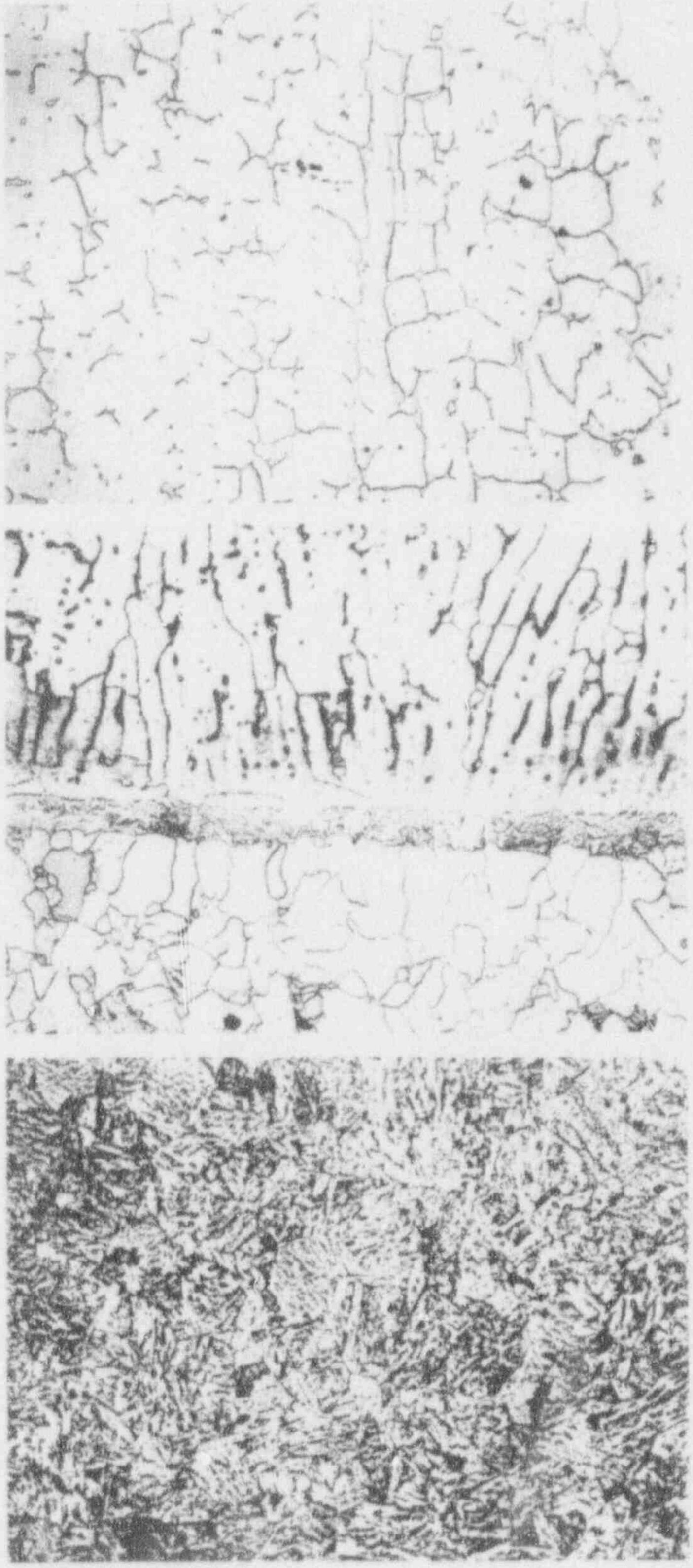


TMIG-24 (900°C/100 min.) U91 0240

50μm

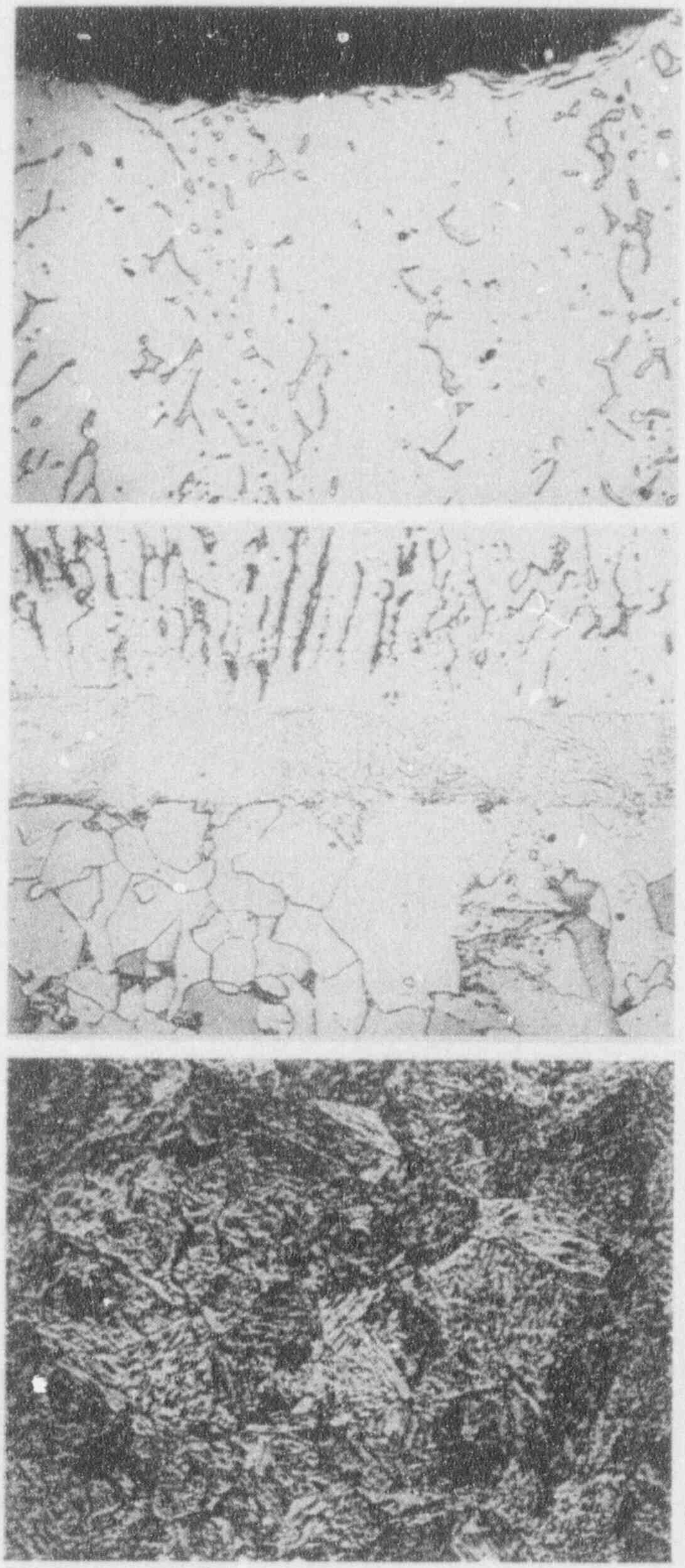


TMIG-17 (1000°C/1 min.) U91 0233



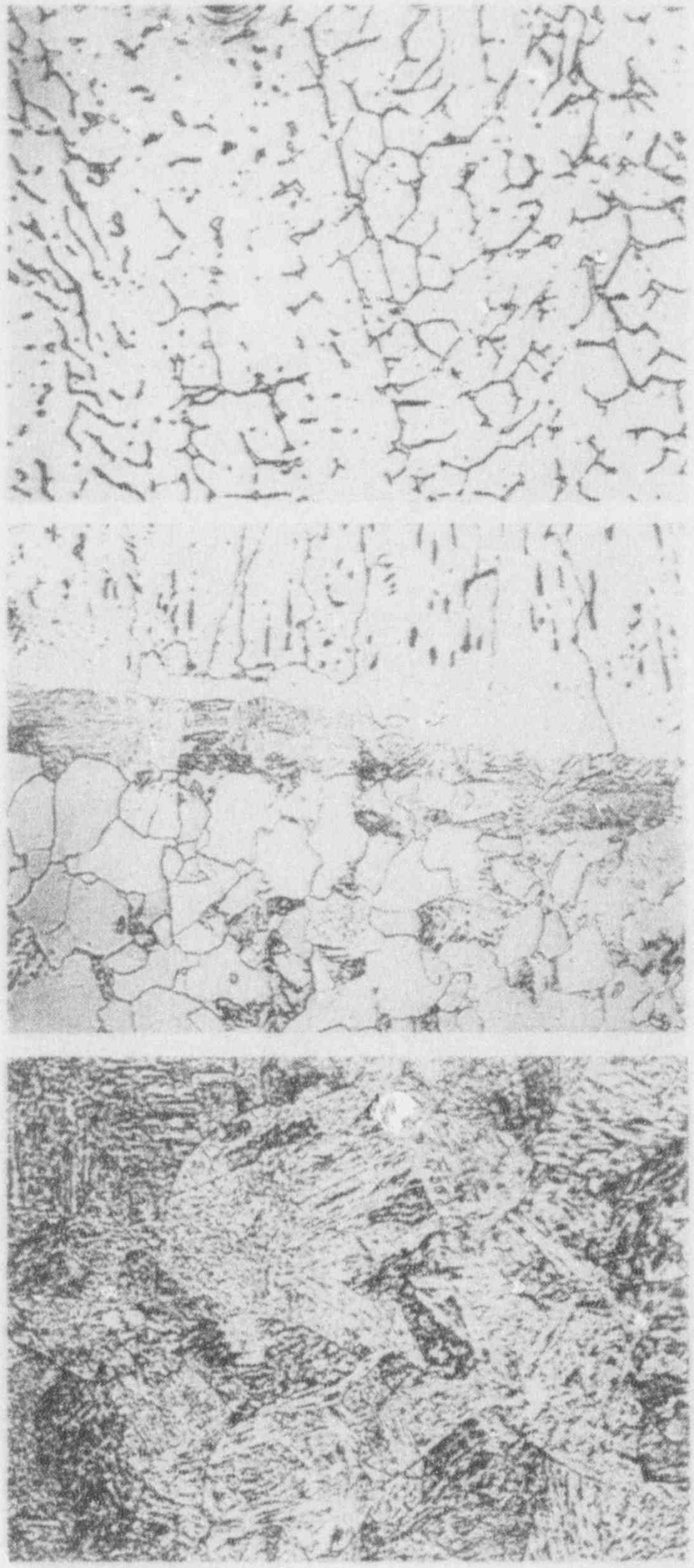
TMIG-21 (1000°C/10 min.) U91 0237

50μm



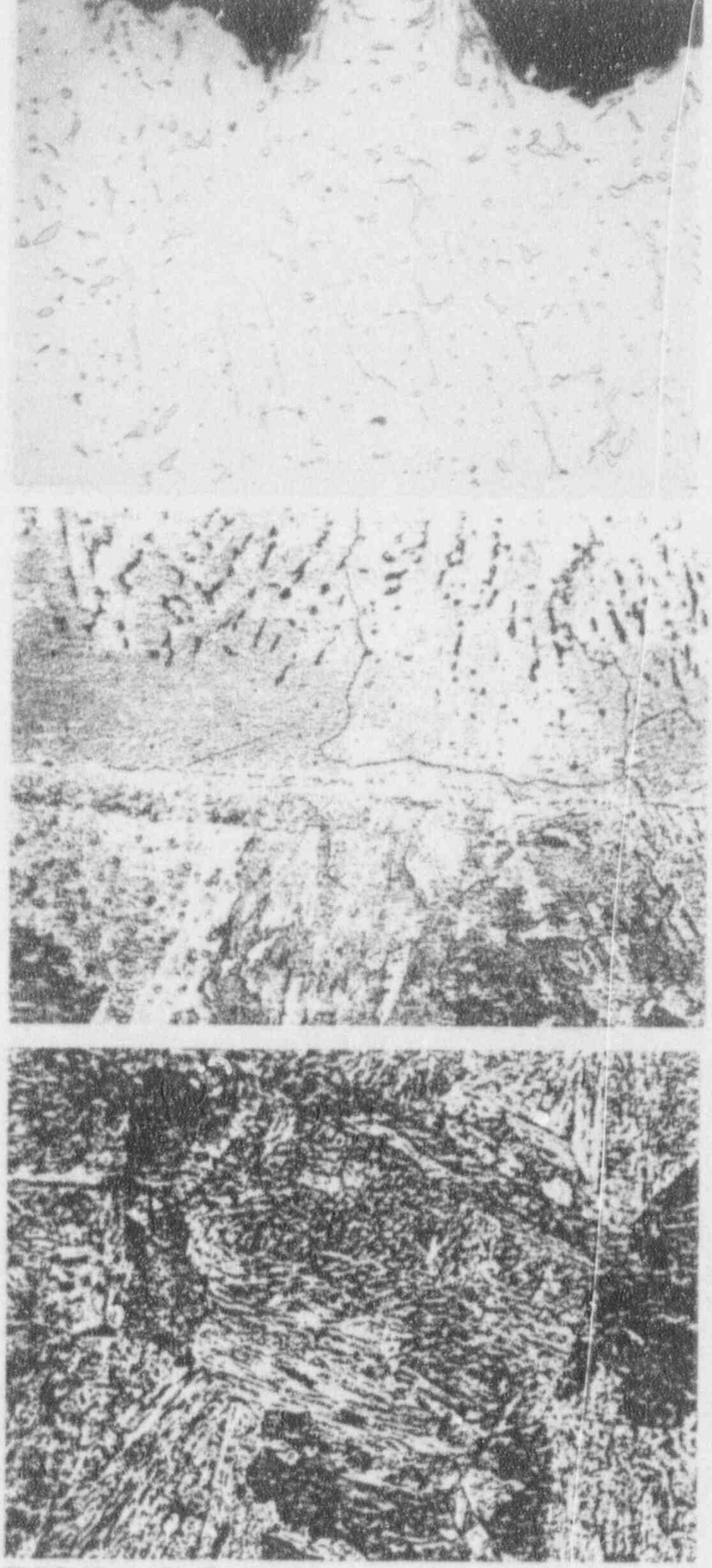
TMIG-25 (1000°C/100 min.) U91 0241

50μm



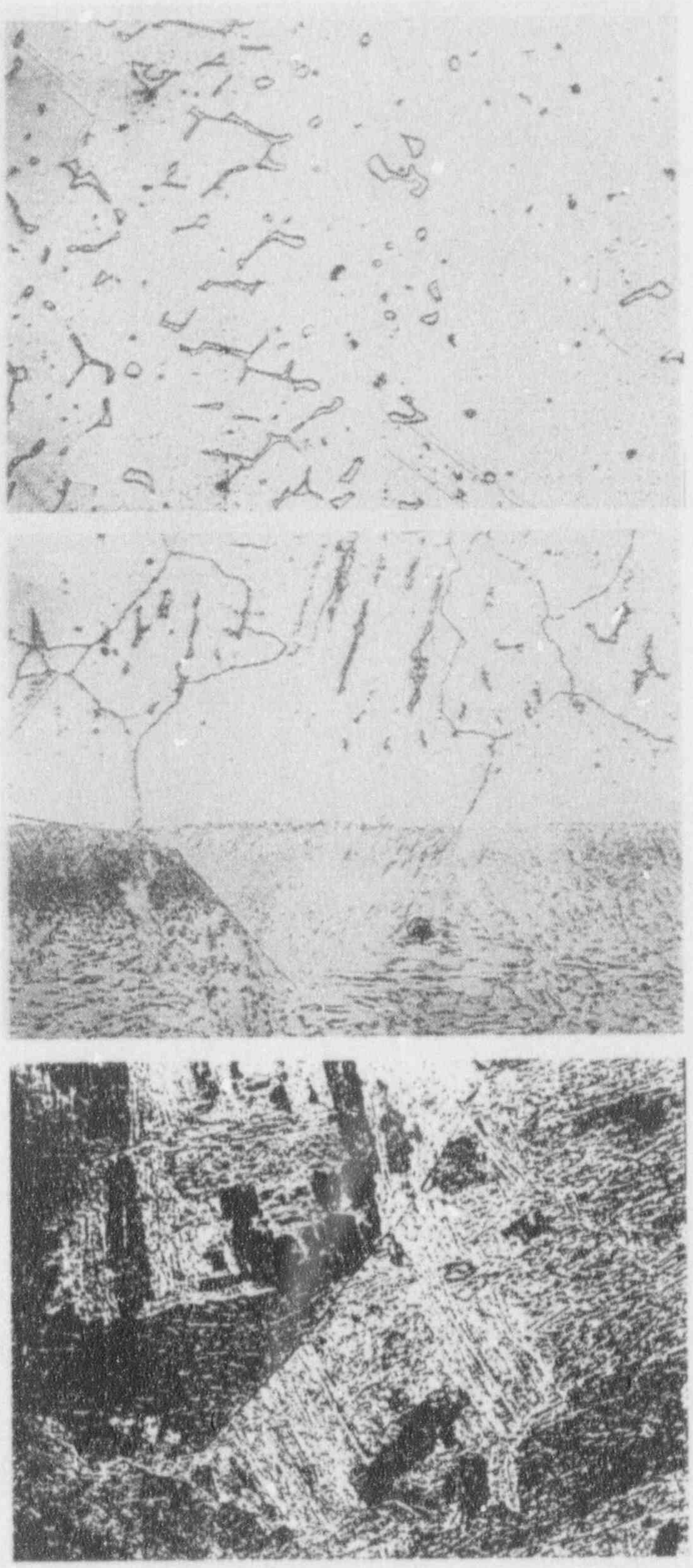
TMIG-18 (1100°C/1 min.) U91 0234

50μm



TMIG-22 (1100°C/10 min.) U91 0238

50μm

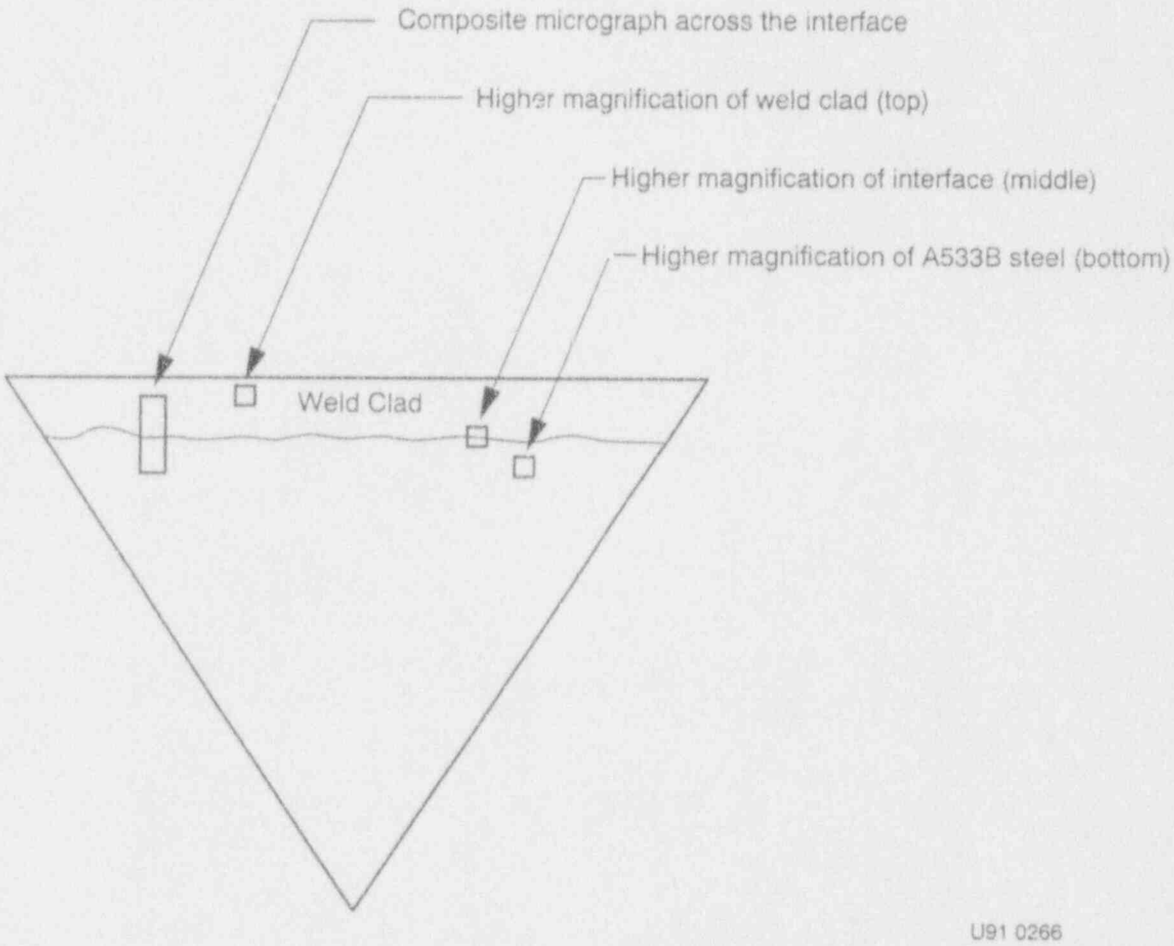


TMIG-26 (1100°C/100 min.) U91 0242

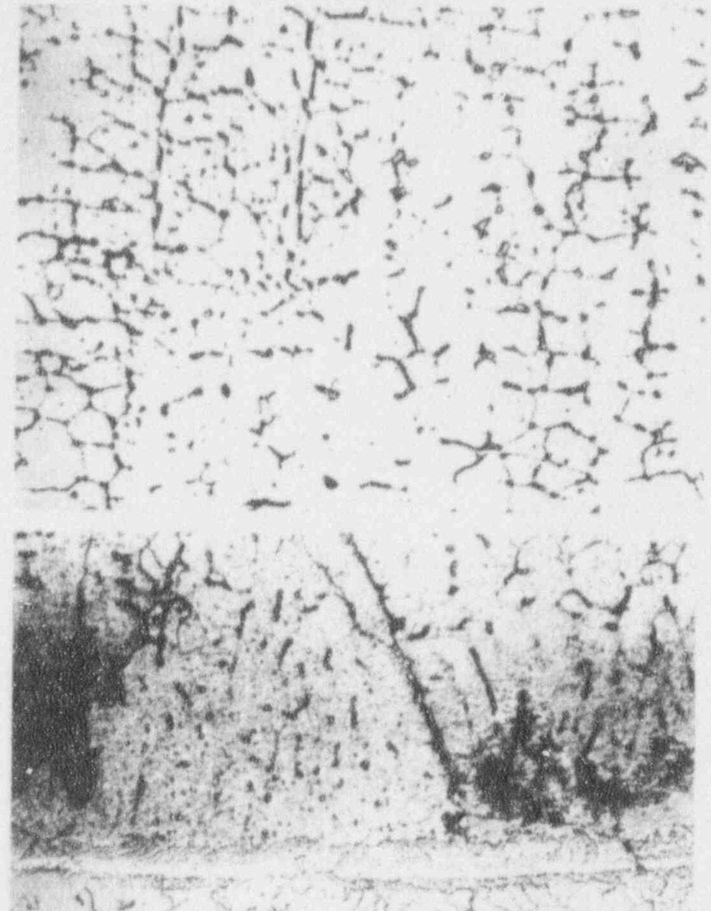
50μm

Appendix C

Microstructure of TMI-2 Samples F-10(M-3), E-8(M-3), G-8 (408P-3), E-6 (402A-1), and Accident-Simulated Heat Treated Slices of Samples H-4(M-3) and M-11(M-3)

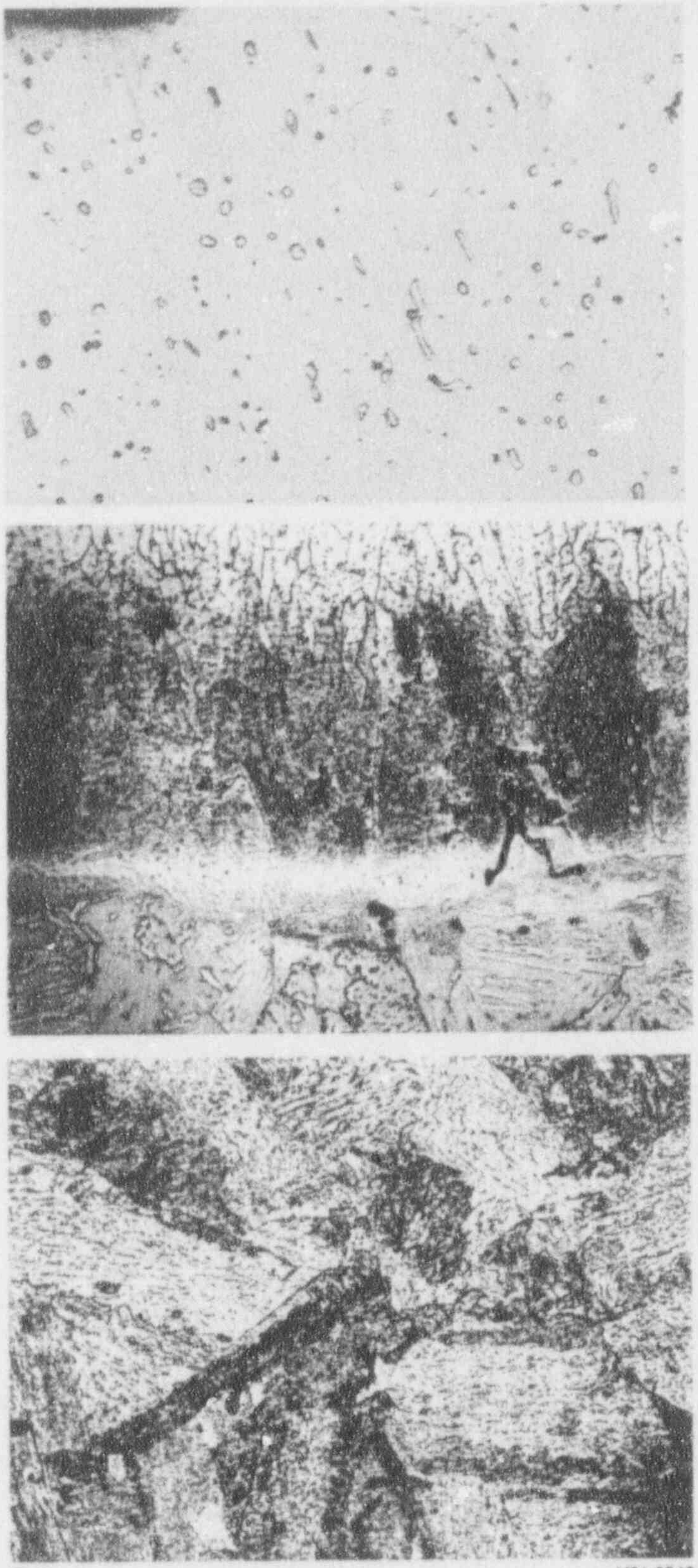

Composite micrograph across the interface
Higher magnification of weld clad (top)
Higher magnification of interface (middle)
Higher magnification of A533B steel (bottom)
Weld Clad
U91 0266


F-10
E-8
U91 0243
200µm



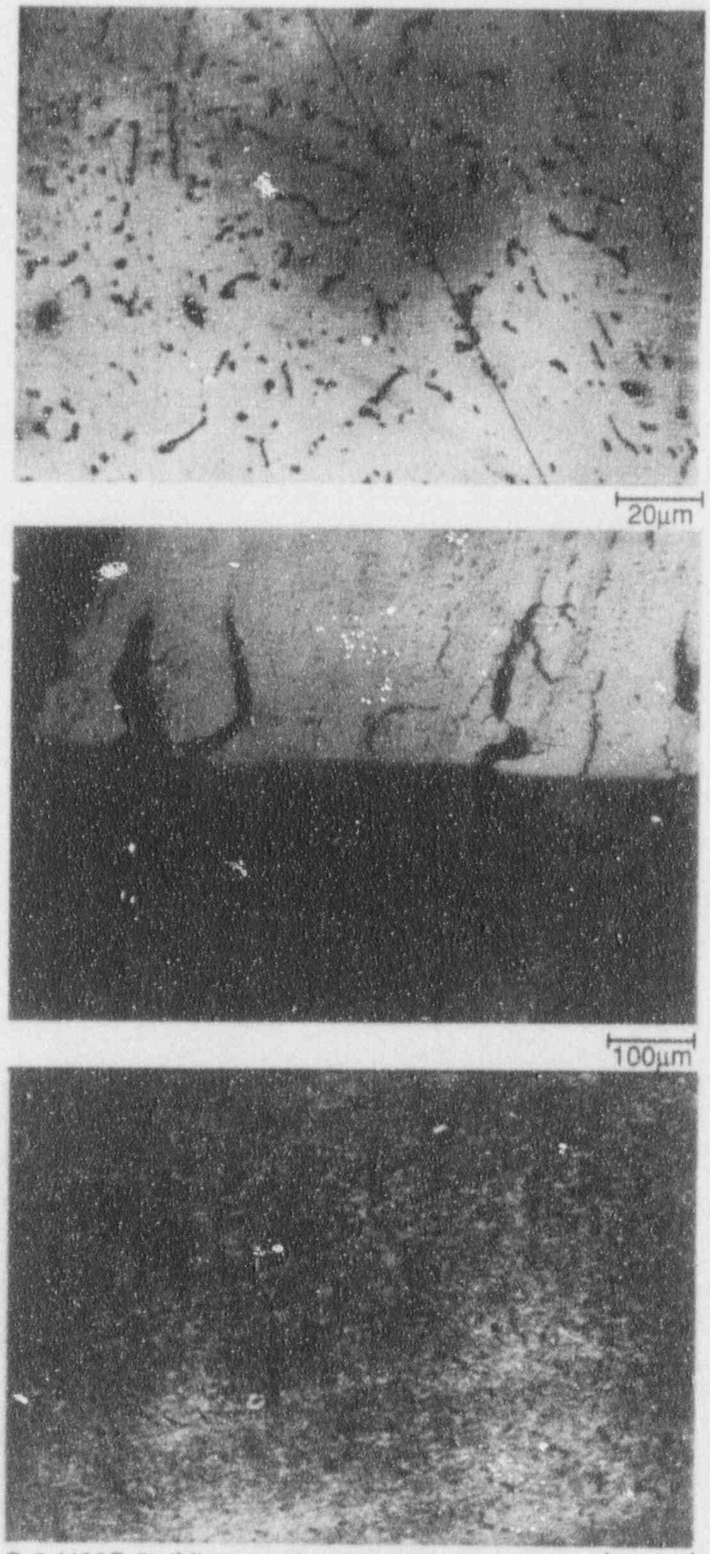
F-10 U91 0244

50μm



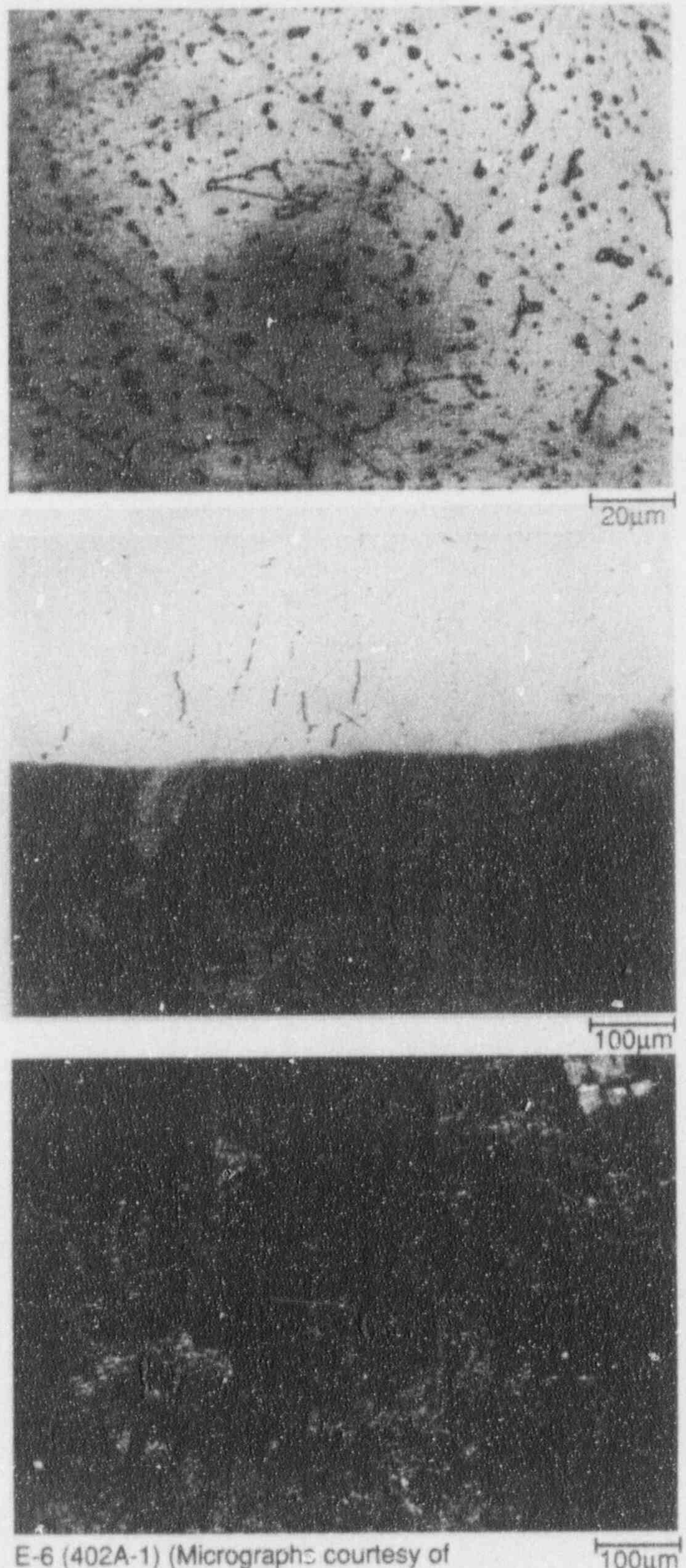
E-8 U91 0245

50µm



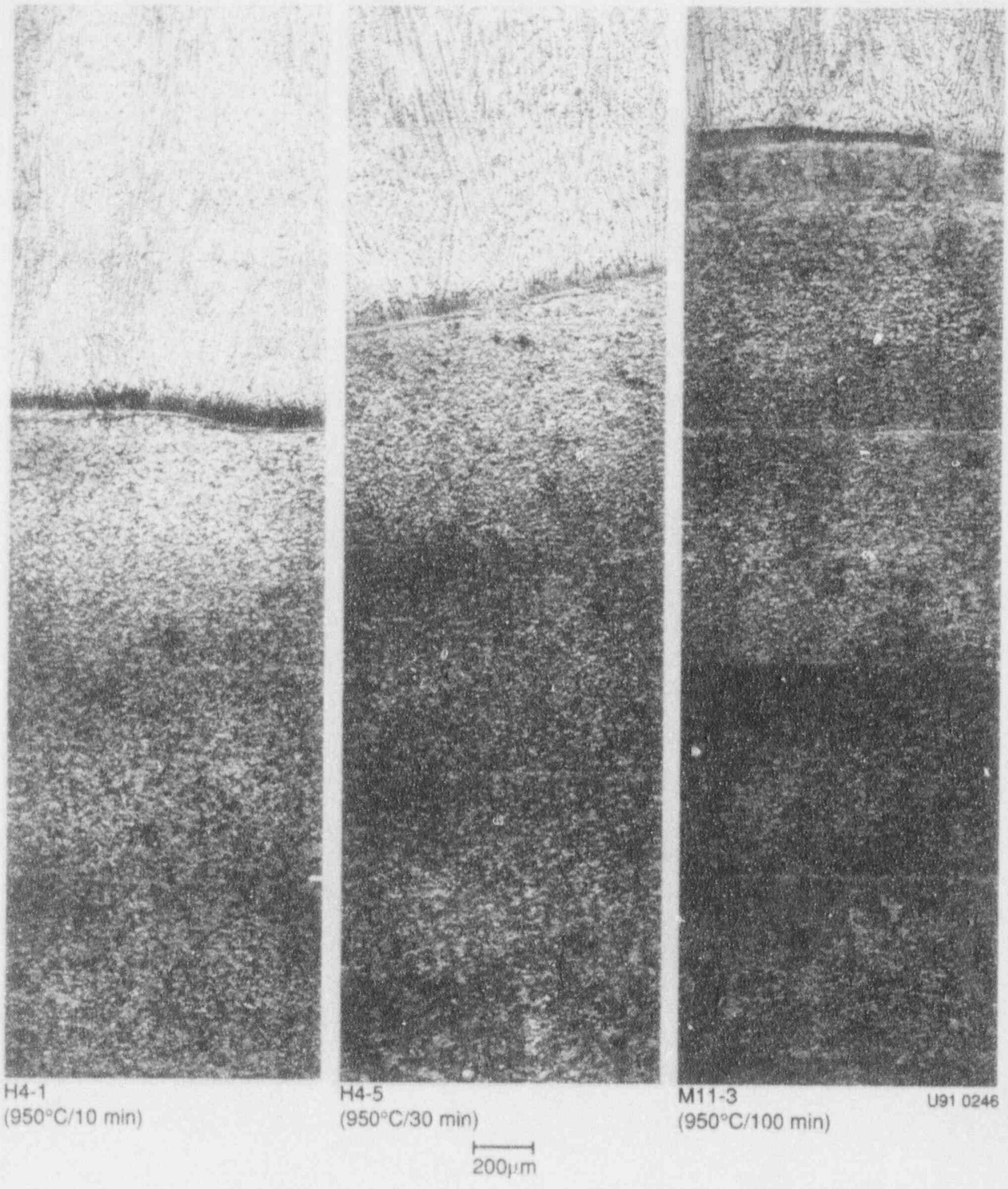
G-8 (408P-3) (Micrographs courtesy of D.R. Diercks, Argonne National Laboratory)

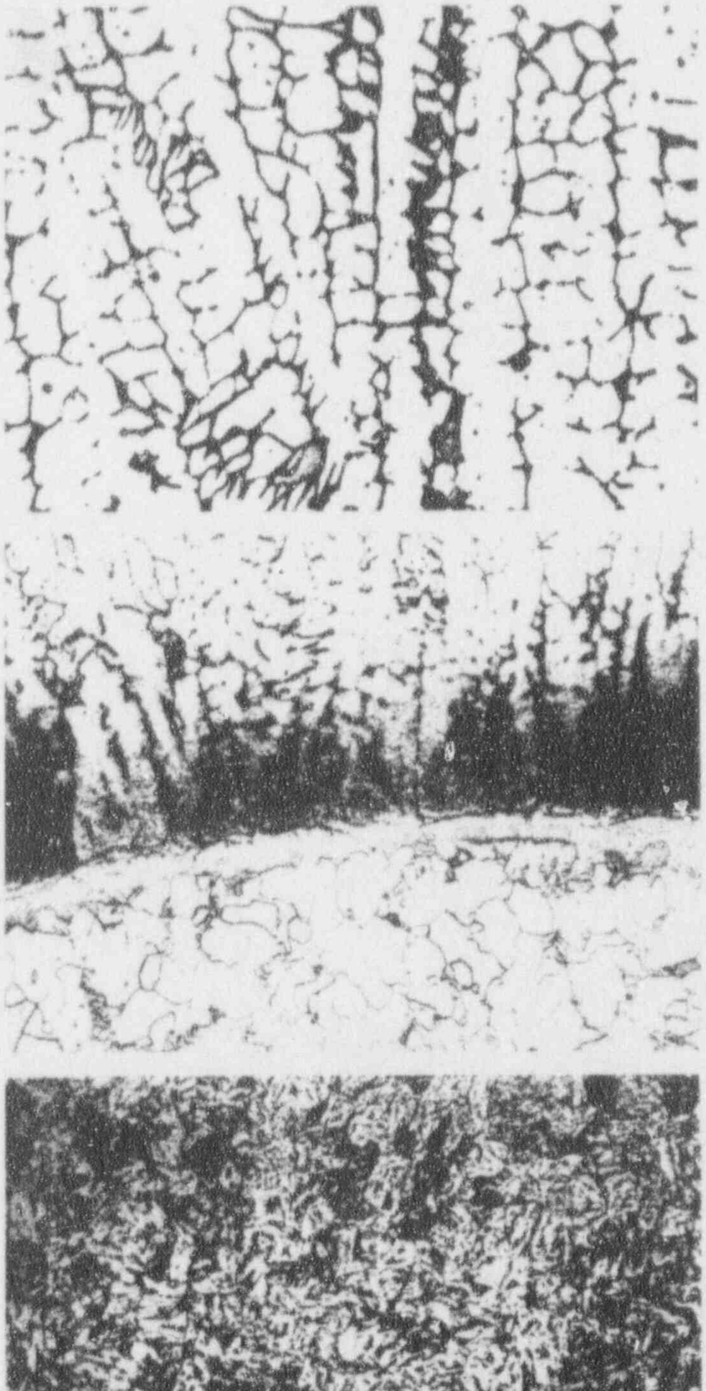
U91 0268



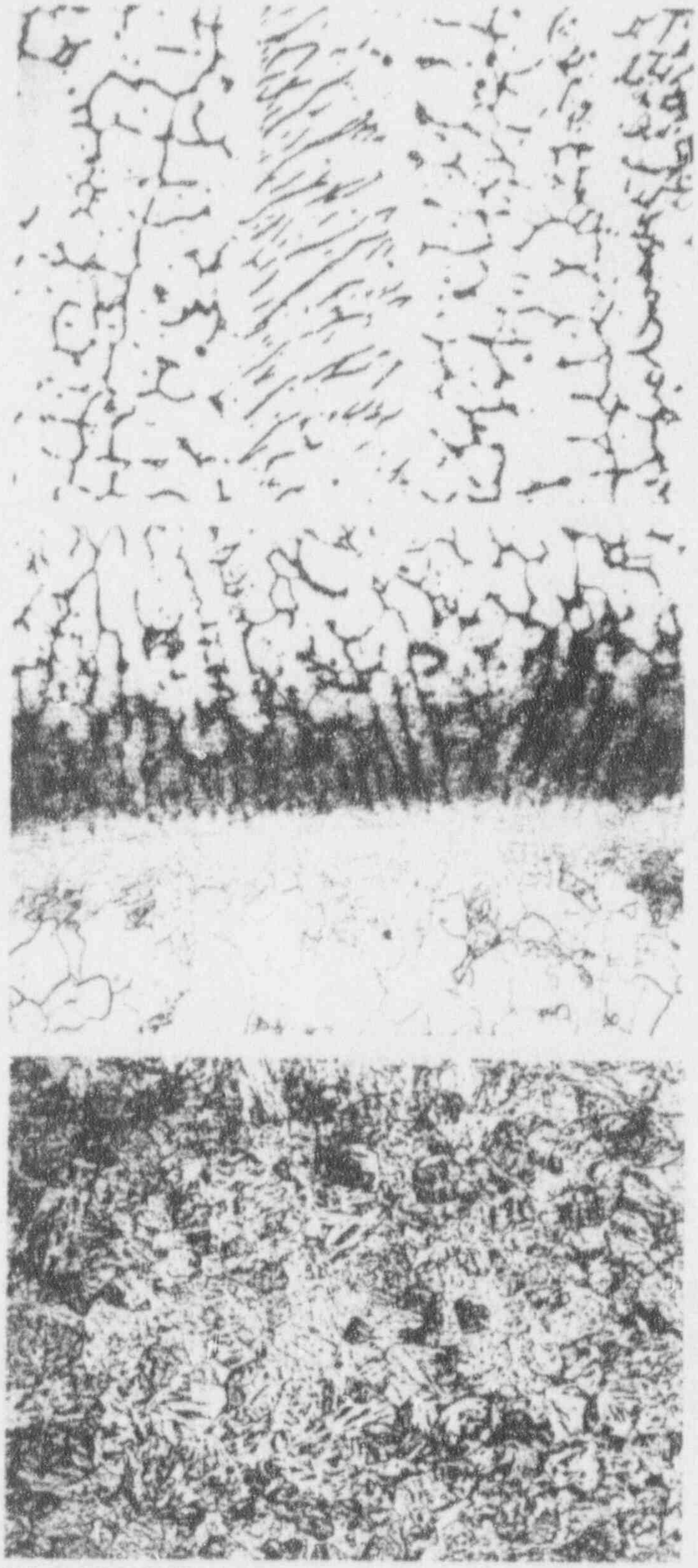
E-6 (402A-1) (Micrographs courtesy of D.R. Diercks, Argonne National Laboratory)

U91 0267


H4-1
(950°C/10 min)
H4-5
(950°C/30 min)
M11-3
(950°C/100 min)
U91 0246
200μm

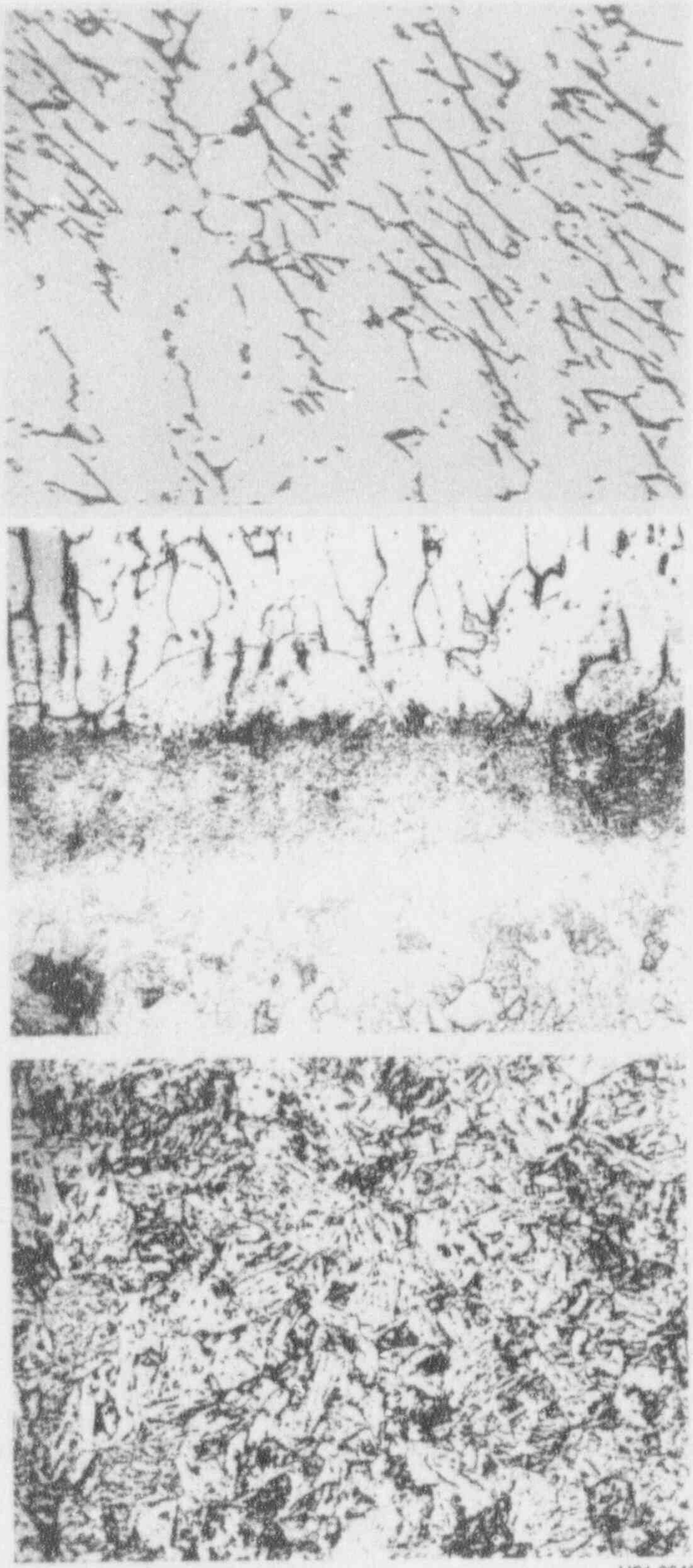


H4-1 (950°C/10 min)



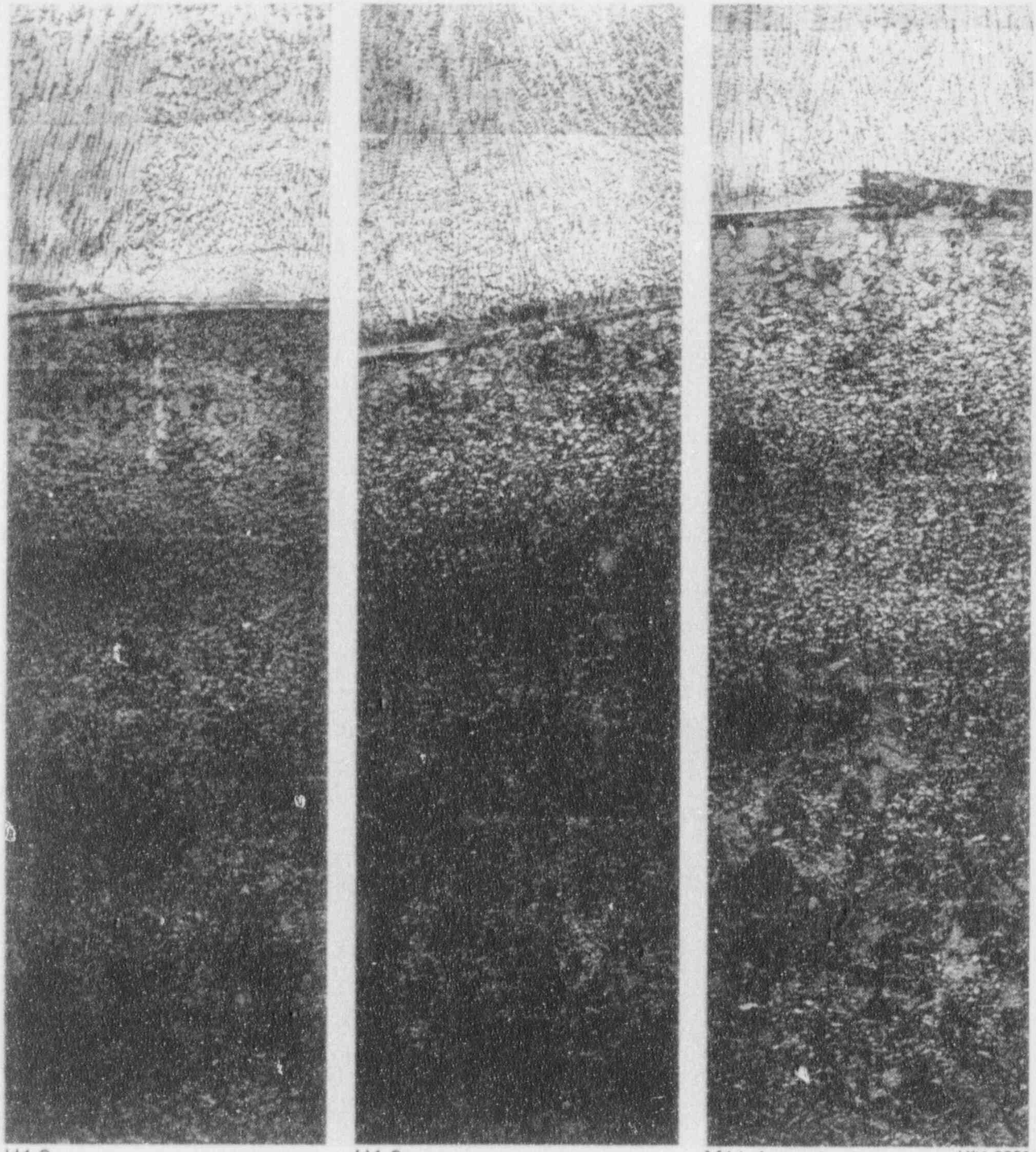
H4-5 (950°C/30 min) U91 0248

50μm



M11-3 (950°C/100 min) U91 0249

50μm

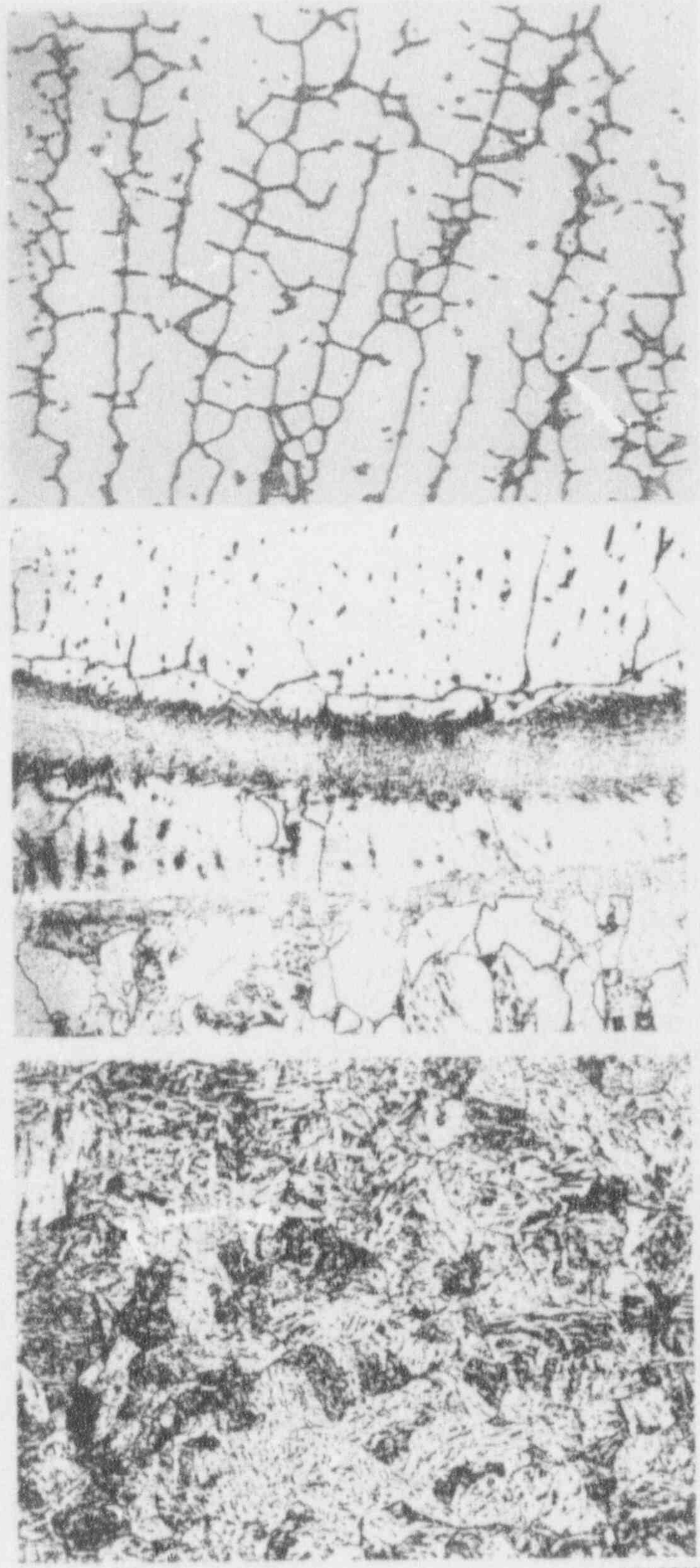

H4-2
(1000°C/10 min)

H4-6
(1000°C/30 min)

M11-4
(1000°C/100 min)

U91 0250

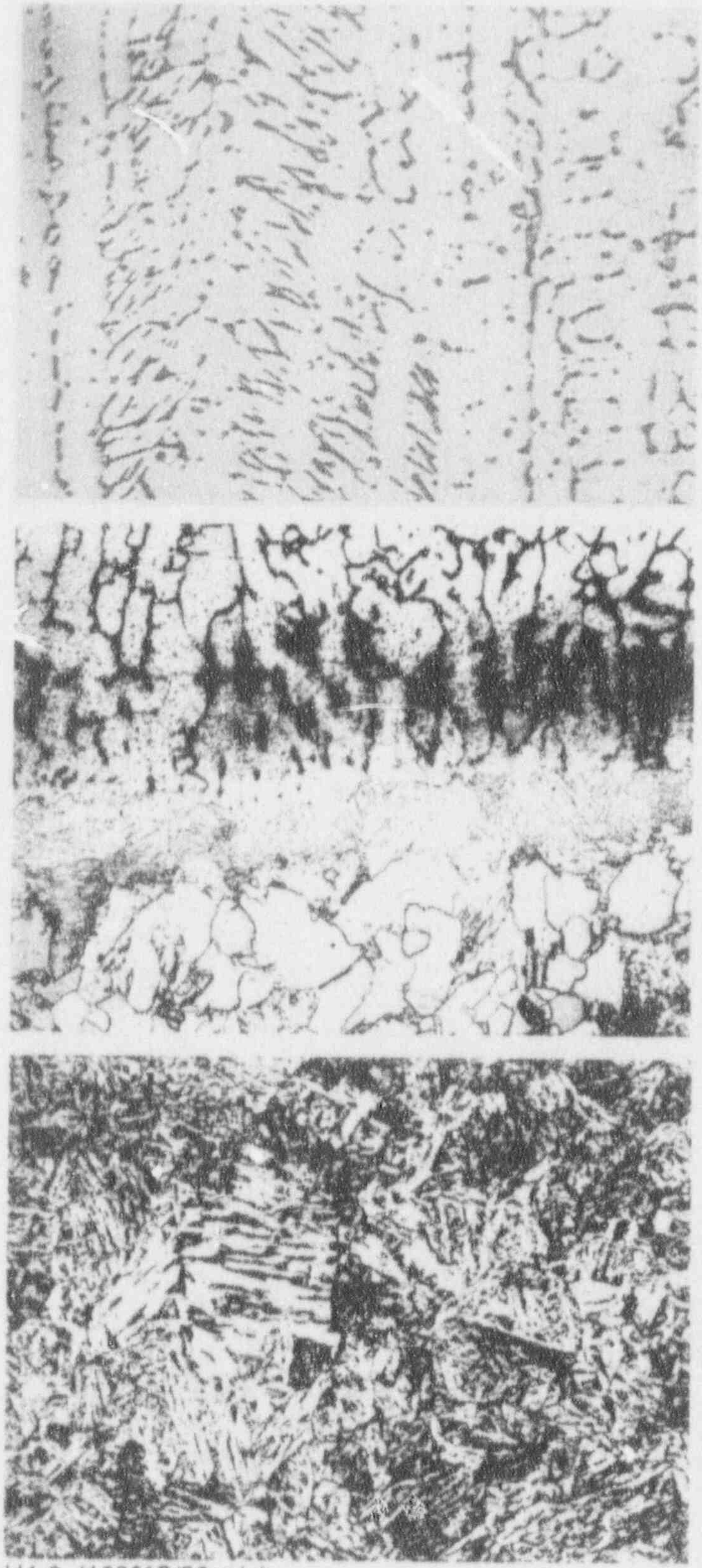
200μm



H4-2 (1000°C/10 min)

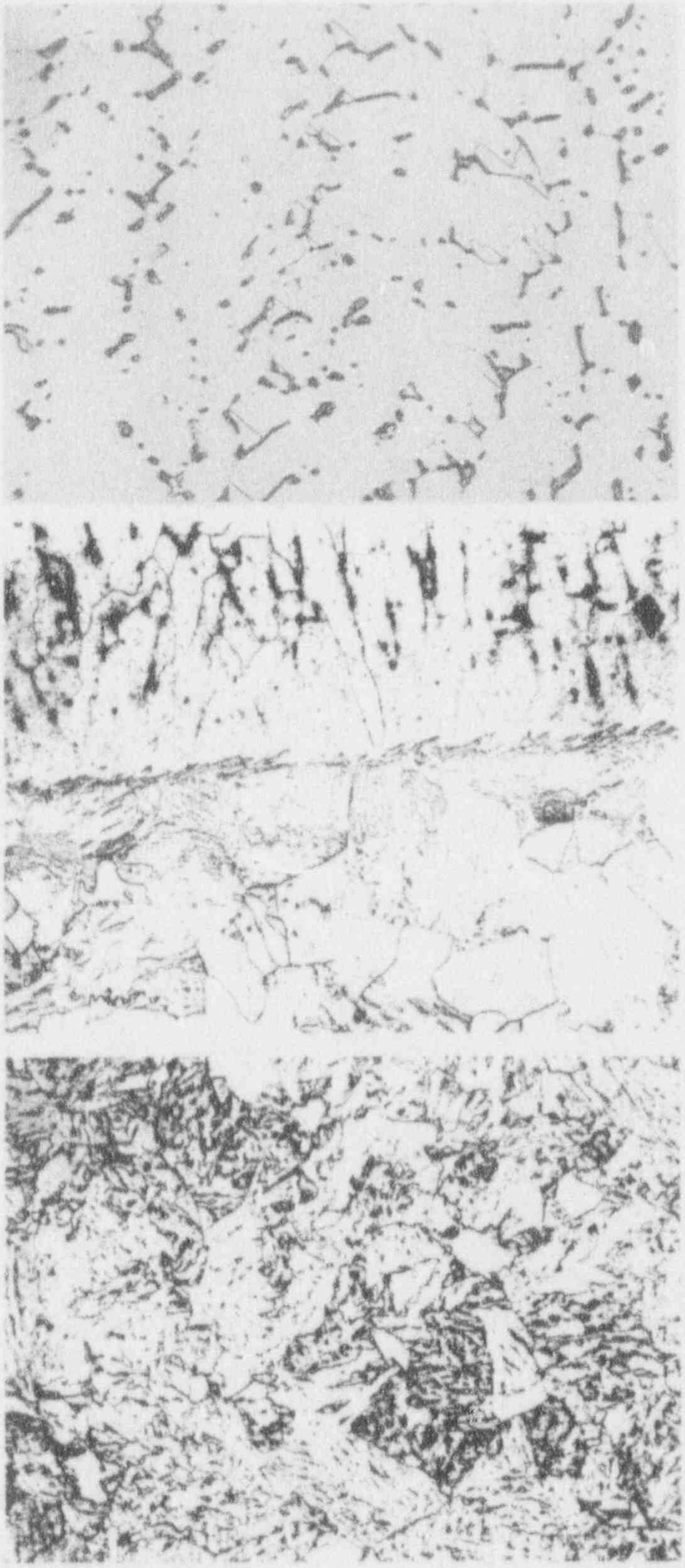
U91 0269

50μm


H4-6 (1000°C/30 min)

U91 0270

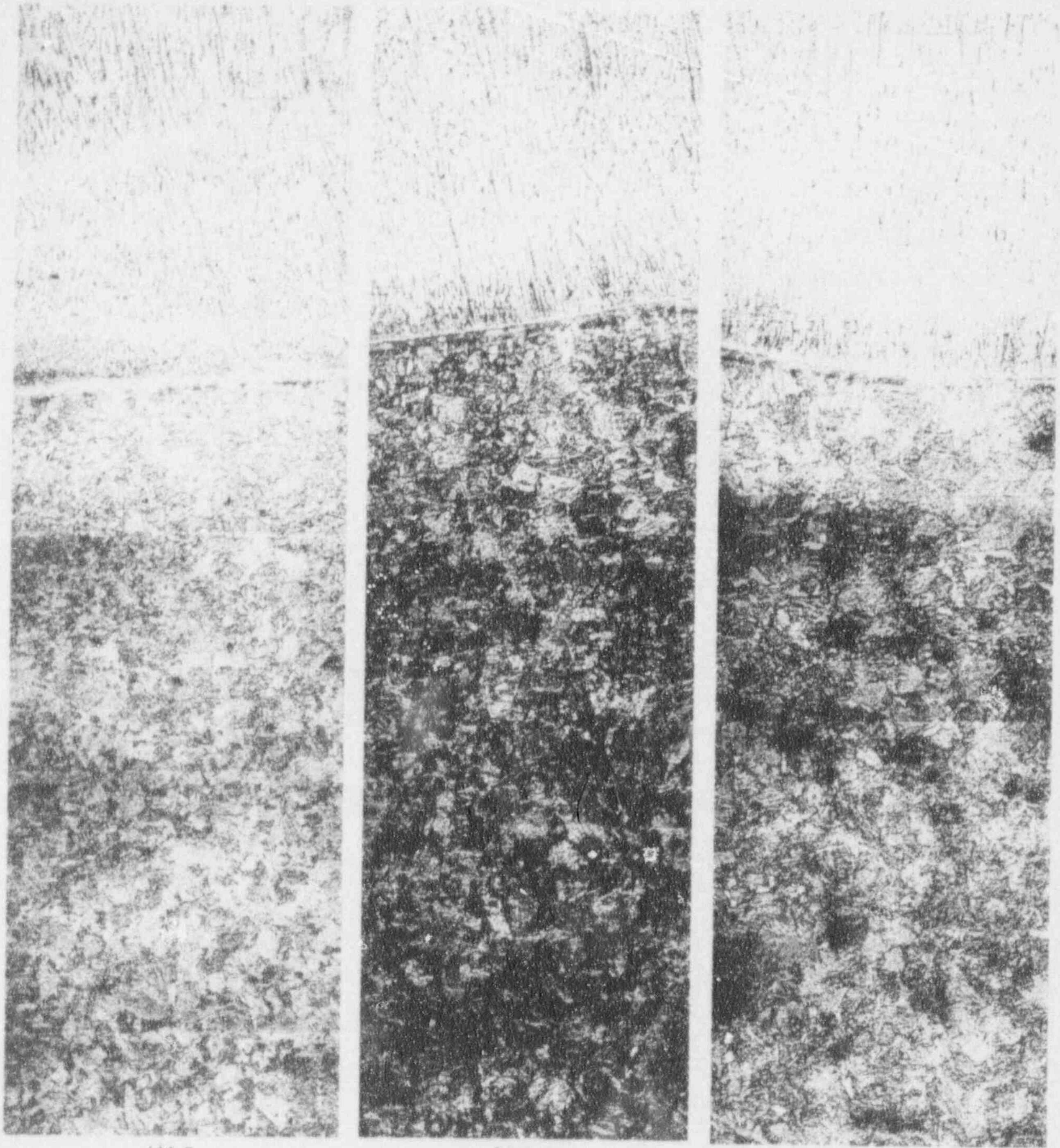
50μm



M11-4 (1000°C/100 min)

U91 0253

50µm

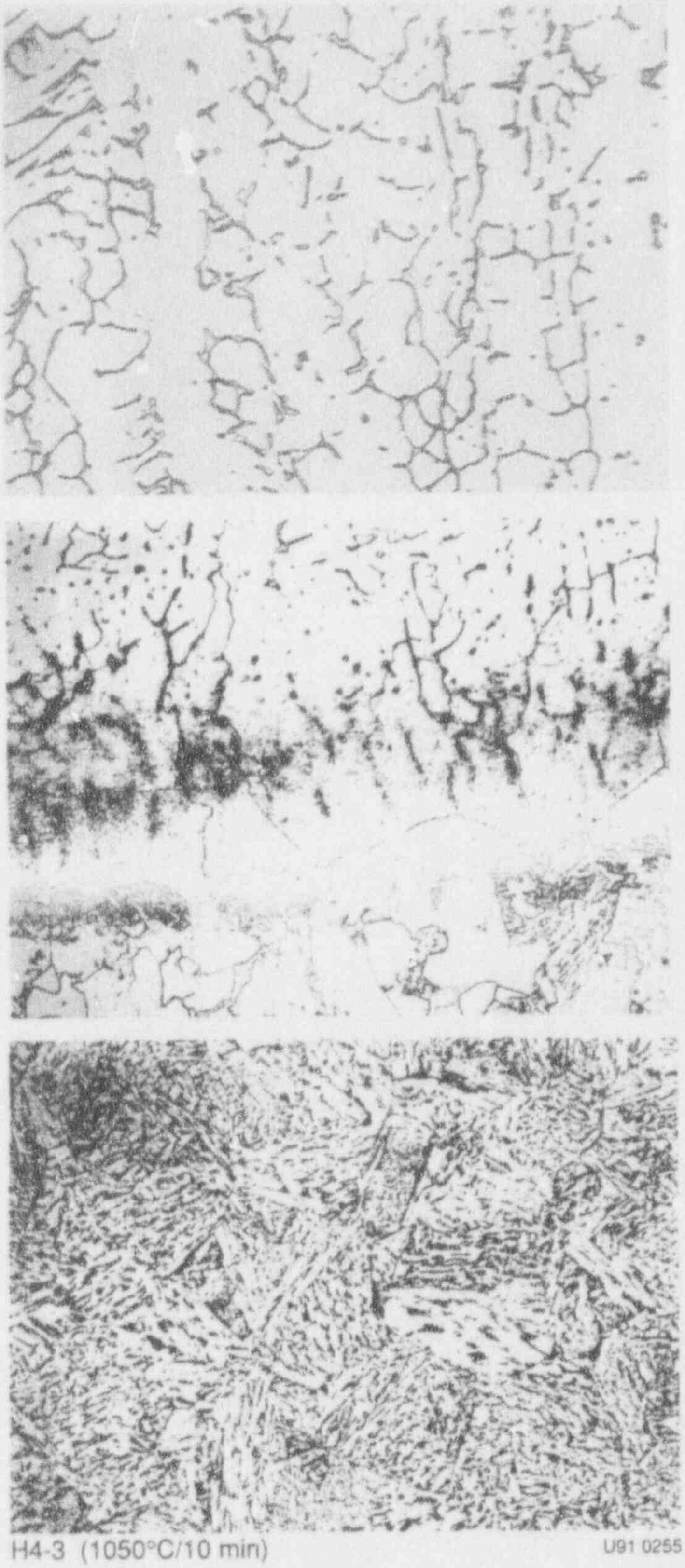


H4-3
(1050°C/10 min)

M11-1
(1050°C/30 min)
200μm

M11-5
(1050°C/100 min)

U91 0254

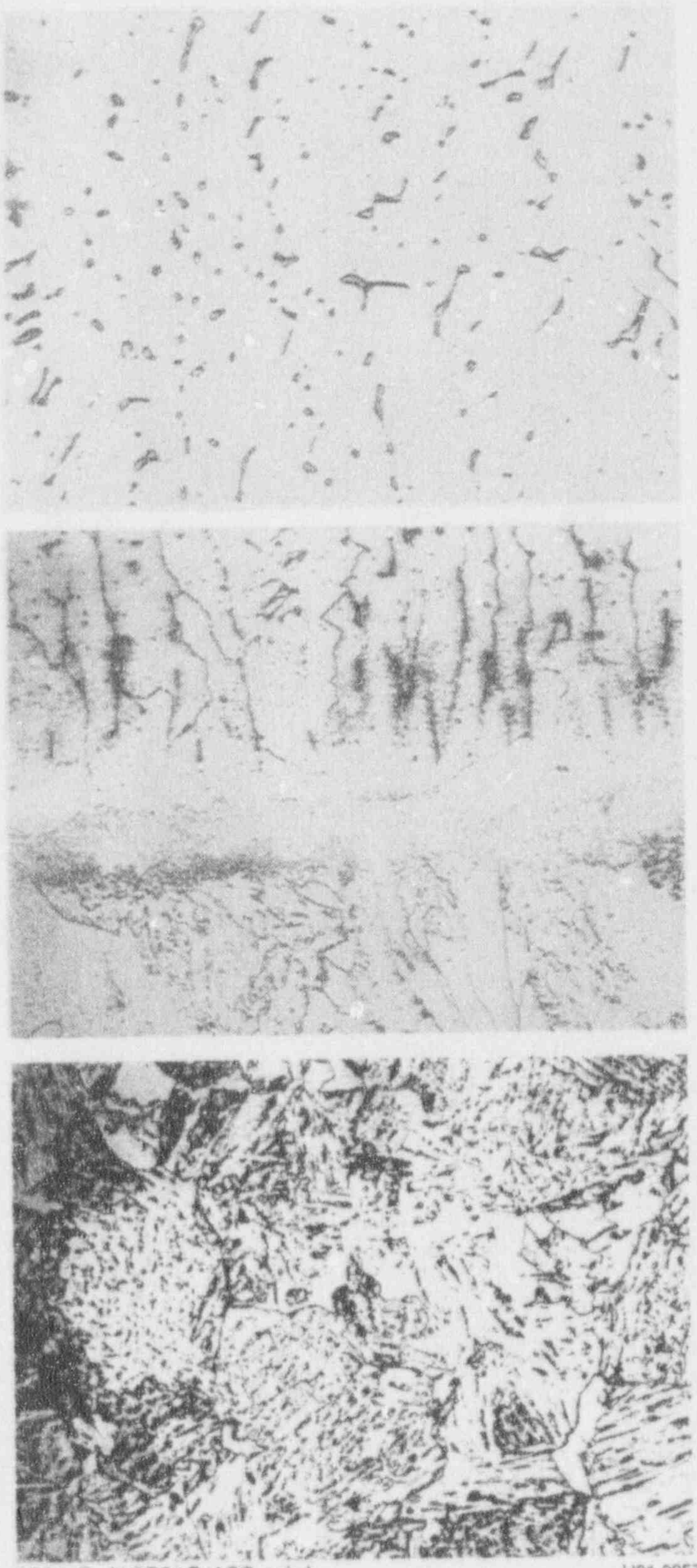


H4-3 (1050°C/10 min) U91 0255

50μm

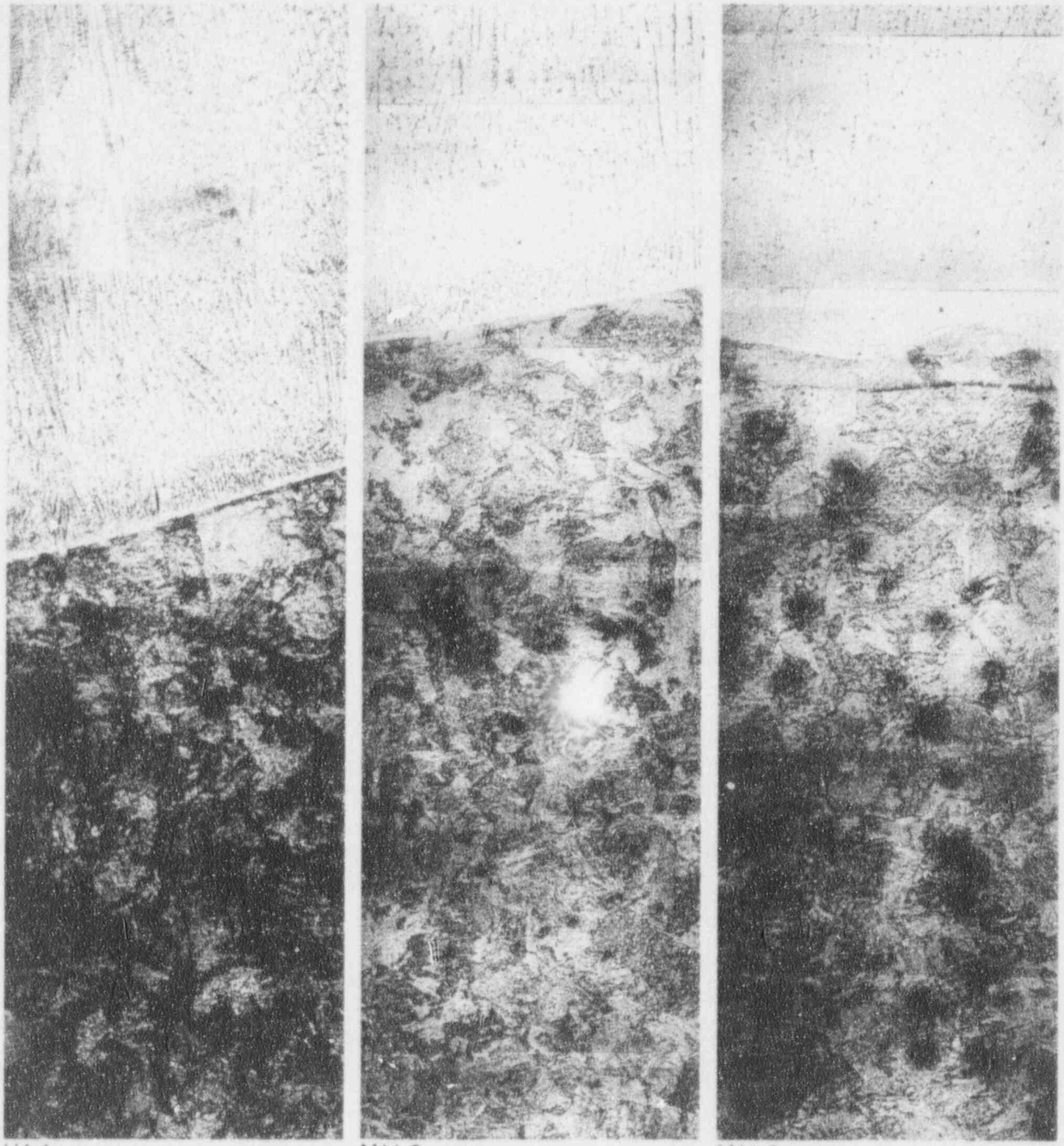
M11-1 (1050°C/30 min) U91 0256

50μm



M11-5 (1050°C/100 min) U91 0257

50μm



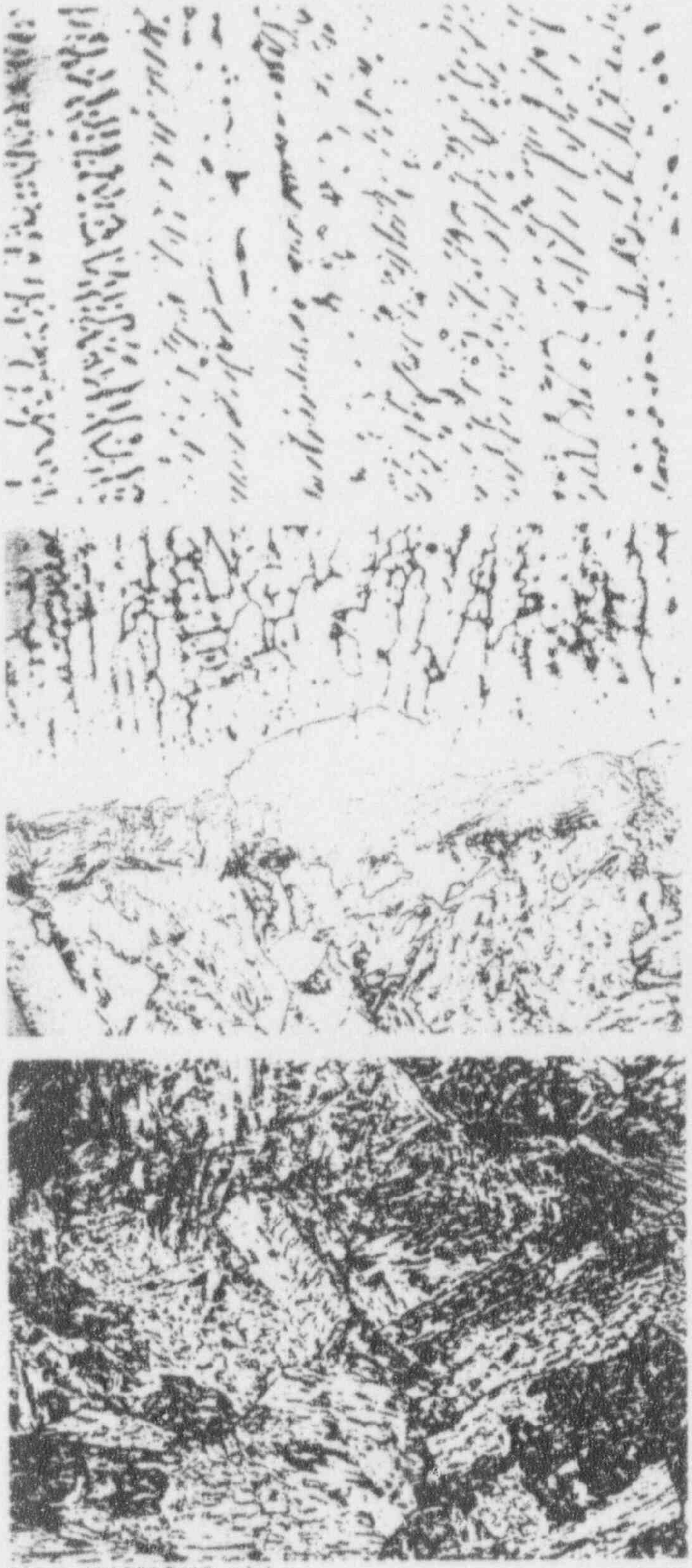
H4-4
(1100°C/10 min)

M11-2
(1100°C/30 min)

M11-6
(1100°C/100 min)

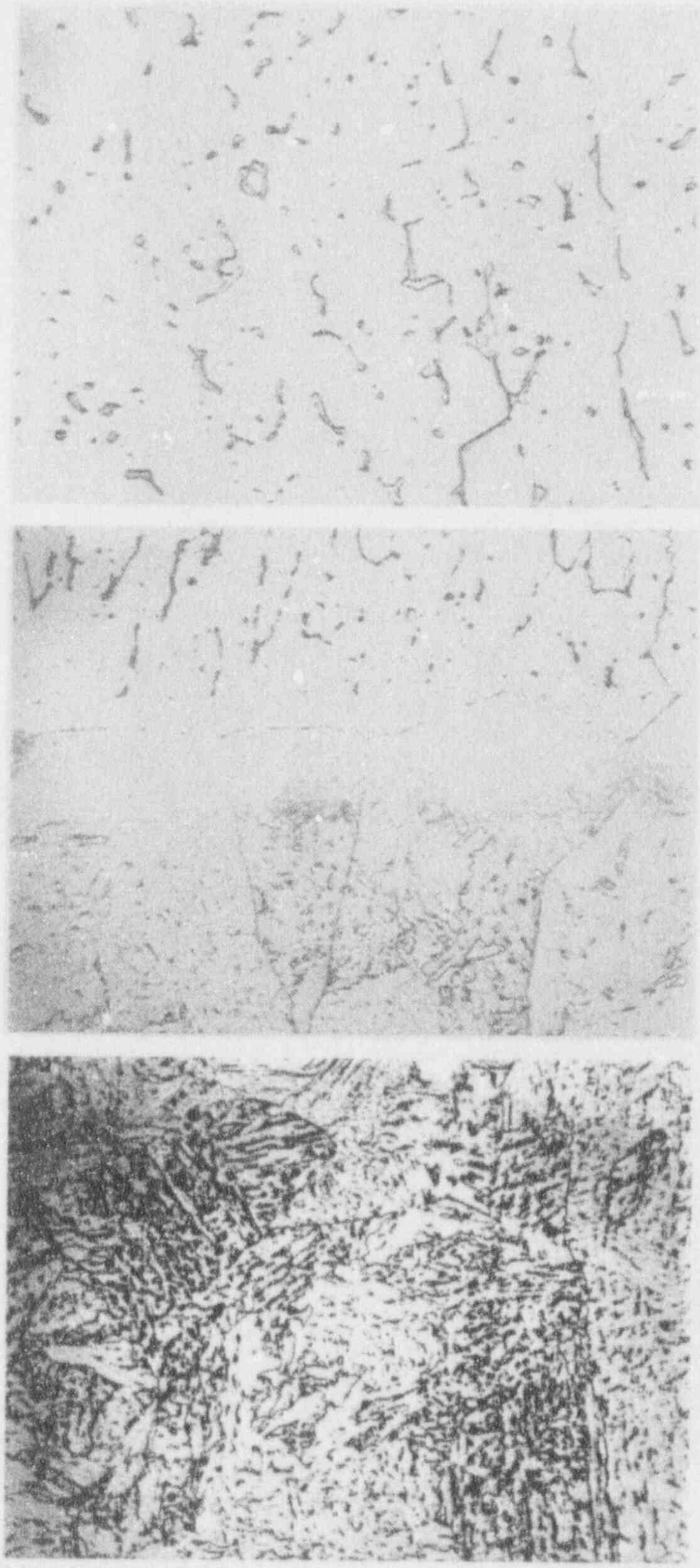
U91 0259

200μm



H4-4 (1100°C/10 min) U91 0260

50μm



M11-2 (1100°C/30 min) U91 0262

50μm

M11-6 (1100°C/100 min) U91 0263

50μm

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Fifteen steel samples were removed from the lower pressure vessel head of the damaged TMI-2 nuclear reactor to assess the thermal threat to the head posed by 15 to 20 metric tons of molten core debris relocating there during the accident. Full sections of thirteen of the samples and partial sections of the other two samples underwent hardness and metallographic examinations at the Idaho National Engineering Laboratory. These examinations have shown that eleven of the fifteen samples did not exceed the ferrite-austenite transformation temperature of 727°C during the accident. The remaining four samples did show evidence of having a much more severe thermal history. The samples from core grid positions F-10 and G-8 are believed to have experienced temperatures of 1,040 to 1,060°C for about 30 minutes. Samples from positions E-8 and E-6 appear to have been subjected to 1,075 to 1,100°C for approximately 30 minutes.

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