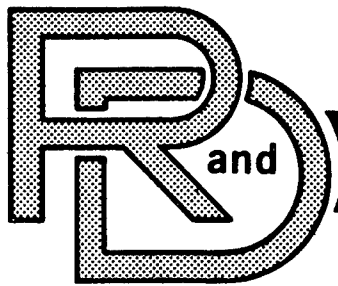


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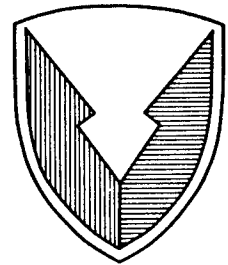
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TECHNICAL REPORT

NO. 13133

RESIDUAL STRESS MEASUREMENTS
ON M1 TANK WELDMENTS
SEPTEMBER 1985



S. B. Catalano
U.S. Army Tank-Automotive Command
ATTN: AMSTA-RCM
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by _____

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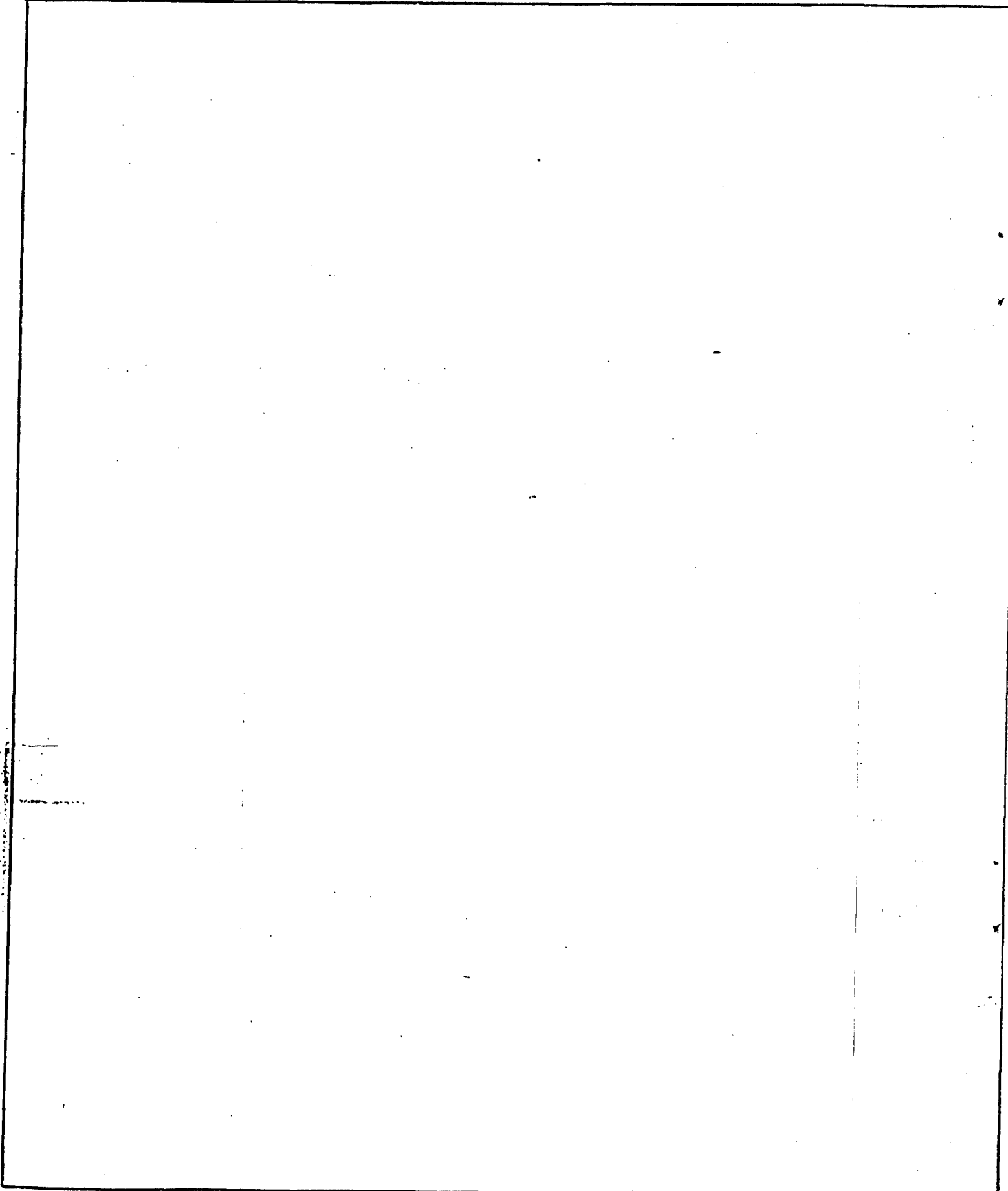
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<ul style="list-style-type: none"> ● race ring to forward glacis; ● turret roof plate joint; ● gunner primary sight to frontal slope plate; and ● side plate to front portion of hull. 				
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PREFACE

This effort was funded under the Manufacturing Methods & Technology (MM&T) program "M1 Residual Stress (Welding Process)" for the Manufacturing Technology Branch (AMSTA-TMM), TACOM, Warren, Michigan. It was a six-month effort covering the period 1 April through 30 September 1985. Appreciation is extended for the privilege and opportunity of working on this challenging project.

Dr. Herbert Dobbs, Technical Director, R&D Center, TACOM, is to be thanked for his interest in this work. Mr. Donald Cargo, Director for Design and Manufacturing Technology, TACOM, is to be thanked for his invitation to work on this project and for his interest and timely support. Messrs. B.A. Schevo, D. Pyrcce, and G. MacAllister are to be thanked for their advice and direction. Messrs. T. Dean and D. Kendal are to be thanked and complimented for their expedience in locating and providing access to M1 tanks at the Lima Army Tank Plant, Lima, Ohio and at the General Dynamics Groesbeck facility in Warren, Michigan for this study. Acknowledgements are also extended to Mr. P. Gherian, Q.A. Engineer, Lima Army Tank Plant for activities performed as the point of contact in arranging for time and space to perform required measurements on M1 tanks in the General Dynamics Plant, Lima, Ohio. Appreciation and thanks are extended to Mr. C. Lambright, American Analytical Corp., for diligence in performing the contracted effort in the measurement of residual stresses with portable X-ray diffraction equipment.

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1.0. INTRODUCTION

1.1. Residual Stress

Stresses remaining within a material after all external forces have been removed are termed residual stresses. Certain operations (e.g., heat treatment, welding, rolling, drawing, forging, casting, machining, sand-blasting, shot-blasting, shot-peening, etc.) performed on a metal part can leave it in a stressed condition which persists in the absence of external forces. Measurements performed at the U.S. Army Tank-Automotive Command (TACOM), Warren, MI, on T-142 track pins illustrate the effect manufacturing processes such as furnace-hardening, induction-hardening, straightening, grinding and shot-peening have on surface residual stress of the pin.¹ Residual stresses in materials arise also in service.² Residual stresses can be of an undesirable nature or concentration level, adversely affecting functional performance and durability. Cumulative high residual stresses and high dynamic stresses (in service) may exceed design load limits of the part.

1.2. Residual Stresses in Weldments

Residual stresses are produced in weldments by local thermal expansion, plastic deformation, and subsequent shrinkage upon cooling. Heat-affected areas adjacent to a weld nugget are nearly always areas of tensile residual stress, and can reduce fatigue life of the weldment. With no external forces applied, the weldment is in equilibrium (i.e., not in motion) and tensile residual stresses in the vicinity of the weldment are balanced by compressive residual stresses in regions elsewhere in the weldment. Measurements performed at TACOM on a cross-section of the weldment illustrate the location of tensile and compressive residual stresses in the vicinity of a weld nugget.³ Residual stress isostress lines of said cross-section are shown in Figure 1-1. The heavy weight solid lines designate the zero level of residual stress. The thin weight solid lines designate areas of compressive residual stress. The dashed lines designate areas of tensile residual stress. Since fatigue failures never start in an area under compression, weldment fatigue life can be substantially increased by inducing a surface compressive residual stress (via shot-peening) on weldment surfaces that otherwise would remain tensile.

1.3. M1 Hull and Turret

The hull and turret of the M1 tank are welded structures. Figure 1-2 is a welding isometric drawing of the turret structure (outer roof portion). Figure 1-3 is a welding isometric drawing of the hull structure. Each weldment in the hull and turret is a potential area of surface tensile residual stress.

1.4. Measurement of Residual Stress

Nondestructive measurement of the surface residual stresses can be accomplished with an X-ray diffraction technique. The method used is the Debye-Scherrer powder X-ray diffraction method. The equipment used has been miniaturized and made suitable for nondestructive field measurement of residual stresses. Specifics of the X-ray diffraction method will not be

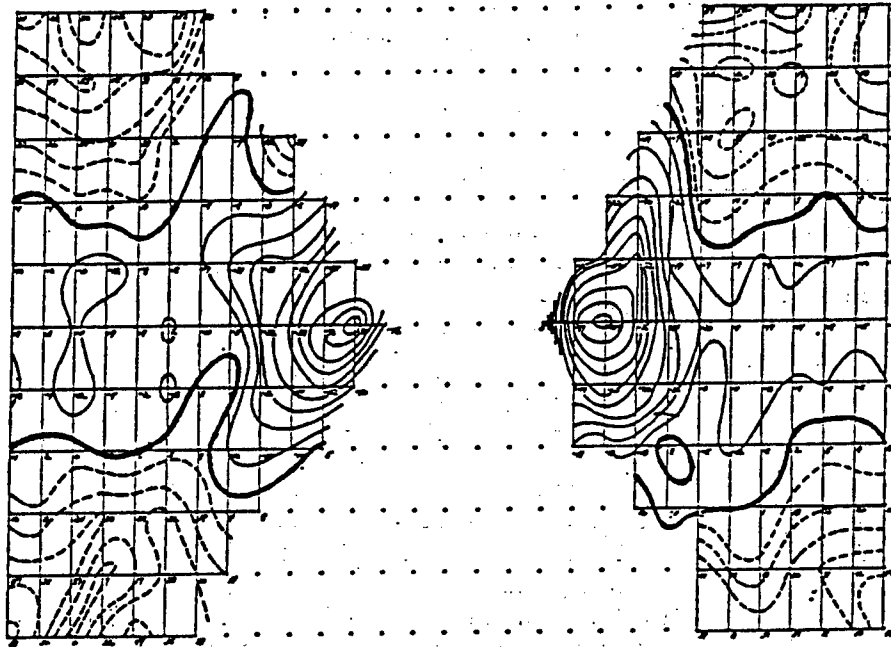


Figure 1-1. Weldment Cross-Section with Residual Stress Isostress Plot

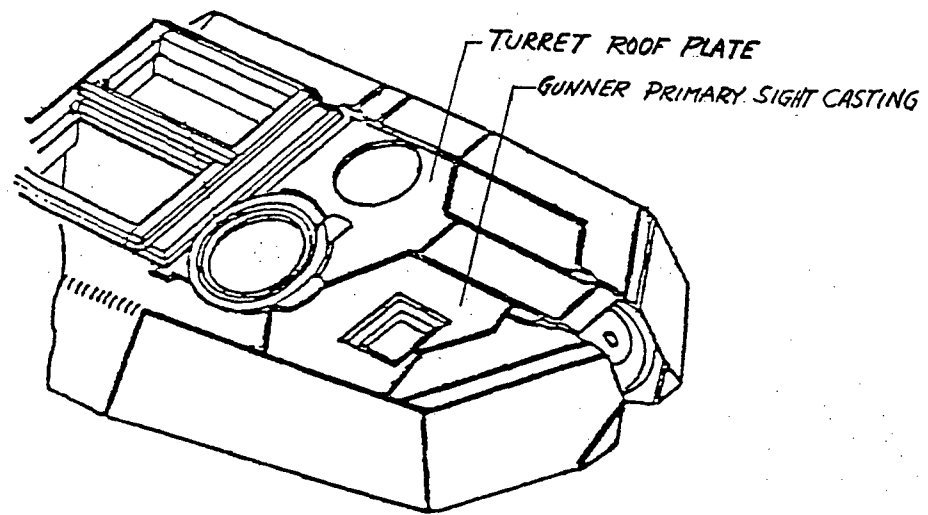


Figure 1-2. M1A1 Welding Isometric Turret Structure; Outer Roof

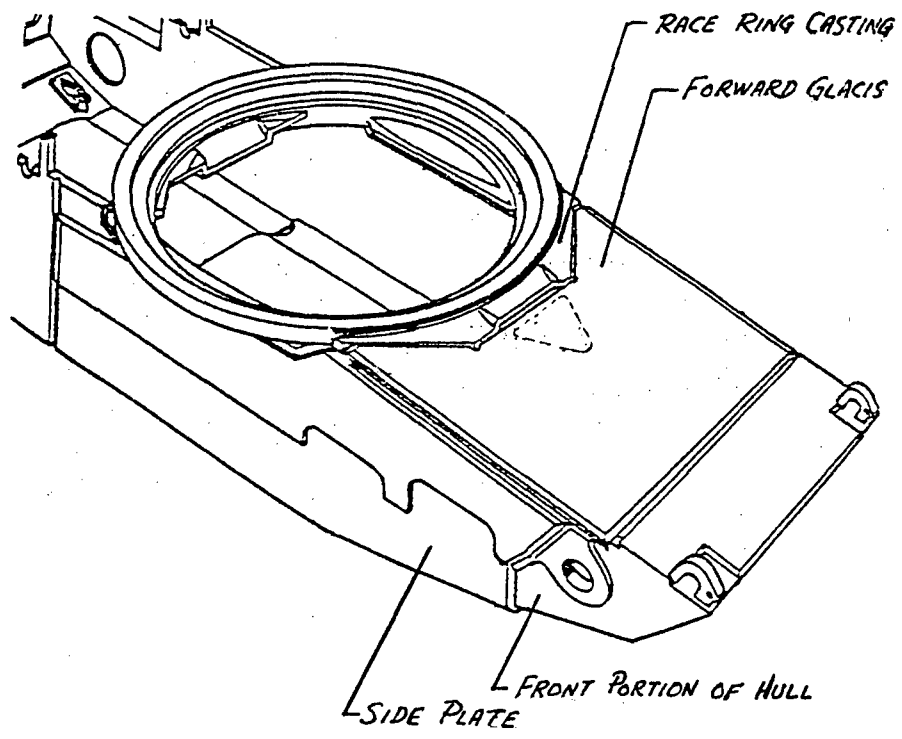


Figure 1-3. M1A1 Welding Isometric, Hull Structure

developed or discussed in detail in this report; the information is plentiful in published text books and open literature. References 2, 4, and 5 are of particular value in this regard. Suffice it here to say that the method uses Bragg's Law: $n \lambda = 2 d \sin \Theta$, where n = an integer, λ = X-ray wave length, d = atomic interplanar spacing, and Θ = the angle of X-ray incidence which results in a reflected diffraction peak. Material strain causes a shift in the value of Θ . Strain may be calculated from the shift in Θ . Through use of elastic theory, strain can be used to calculate stress present, regardless of whether it be residual stress or applied stress. The equipment used in this effort was instrumented with an on-board computer to perform the required calculations.

2.0. OBJECTIVE

The objective of this effort was to measure residual stress level on M1 tank weldments. Measurements were performed on preexisting tanks as well as on current production runs. The weldments selected for measurement were:

- Race ring to forward glacis (roll homogeneous armor to cast armor);
- Gunner primary sight to frontal slope plate (casting to two wrought plates);
- Side plate to front portion of hull;
- Turret roof plate joint.

3.0. CONCLUSIONS

A total of 67 residual stress measurements were performed on early model (preexisting) M1 tanks. Only two of these measurements revealed tensile residual stresses; the rest were compressive. The greatest tensile residual stress level was 13,000 psi; the greatest compressive residual stress level was 134,000 psi. A total of 75 residual stress measurements were performed on current production M1 tanks. Only four of these measurements revealed tensile residual stresses; the rest were compressive. The greatest tensile residual stress level was 47,000 psi; the greatest compressive residual stress level was 154,000 psi. The conclusion to be drawn from these data is that no detrimental level of residual stress was observed on the weldments measured. The tensile readings observed were not of a serious magnitude; the compressive readings observed are beneficial.

4.0. RECOMMENDATIONS

The weldment areas measured in this effort were identified as being the best possible candidates for this study. The X-ray equipment used was state-of-the-art equipment. The contractor (American Analytical Corp.) is one of this country's leaders in the residual stress field. The data obtained indicate no detrimental levels of residual stresses being present in these weldments. These findings support the recommendation that no corrective action is required at this time. It should be pointed out, however, that from

the outset, it was expected that tensile residual stresses would have been observed in heat-affected zones of the weldments. Having observed predominantly compressive readings indicates that factors other than welding process factors may be present. It is believed that said factors are related to other manufacturing processes which follow the welding process. It is known, for example, that the entire hull and entire turret are shot-blast prior to painting to accomplish enhanced paint adherence. Shot-blasting is known to induce compressive residual stresses. If it should become necessary to follow residual stress level as a function of the various processing steps that may be present from welding to painting, it is recommended that a proposal be submitted and funding allocated for this endeavor.

5.0. DISCUSSION

The X-ray measurement of residual stress involved X-ray diffraction techniques. X-ray diffraction differs from X-ray radiography in that it involves surface and near-surface reflections of X-rays; X-ray radiography involves penetration of material thicknesses to form images on films or other detecting systems. Diffraction employs much lower voltages on the X-ray tube as well as different X-ray tube types. The X-ray radiation used in this study is long wavelength, sometimes referred to as soft X-ray and is useful for measuring surface residual stress; it is not at all useful for radiographic purposes. For this reason, special armor configuration was not in jeopardy of being revealed in this work.

5.1. Stress Direction

Residual stress has direction as well as magnitude. Measurement of residual stress in a specified direction with X-ray diffraction equipment is accomplished by rotational orientation/alignment of equipment with respect to the item/part being measured. The stress direction of interest in this effort is perpendicular to the weld nugget since this is the direction of stresses causing typical weldment cracking. All but three of the measurements performed in the work effort reported here were perpendicular to the weld nugget; these three were parallel to the weld nugget.

5.2. Surface Considerations

Fatigue cracking in materials is known to originate at the surface. It is also known that the surface of the heat-affected zone of a weldment can contain high tensile residual stresses; these can, in some cases, be large enough to cause cracking in the heat-affected zone upon cool down after welding. For these reasons, the surface of the weldments in the M1 tank would be of most interest in this M1 weldment residual stress study. However, one should electropolish a few thousandths of an inch of material away prior to measuring stress since the residual stress exactly at the surface would reflect random/extraneous residual stress. Examples of random/extraneously induced residual stresses are those induced by sanding away rust, use of slag hammer, and use of air operated wire peener. In the work effort here, the surface was electropolished from 4 to 10 thousandths of an inch prior to measurement; in a few cases, electropolishing was deeper. Only one measurement was performed without first electropolishing the surface.

5.3. X-ray Beam Size

The isostress plot, referred to earlier in Figure 1-1, illustrates the steep stress gradients present in the vicinity of a weldment. For this reason, a reasonably small diameter X-ray beam should be used when measuring residual stresses in the vicinity of weldments. The trade-off, however, is that longer exposure times are required for smaller X-ray beam sizes. The beam size used in this effort was approximately 1/8 inch in diameter; the exposure times were approximately 5 minutes. Penetration of the beam was only about 1/1000 of an inch. Five readings were taken with a smaller X-ray beam size (using a 0.090 inch collimator). Each residual stress measurement taken is valid only for the weldment area defined by the beam size and penetration depth. For this reason, readings at many different spots are required to characterize the weldment in question.

5.4. Approach

Current production M1 tanks were obtained for this effort from the Lima Army Tank Plant (LATP), Lima, OH. Preexisting M1 tanks were obtained from General Dynamics, Warren, MI. In both cases, the hulls and turrets were separate (i.e., not in the married configuration) and without track. This was accomplished at LATP by intercepting hulls and turrets on the production line after welding, but prior to painting; the preexisting tanks were being refurbished and had already been appropriately disassembled. Paint had to be removed from the preexisting tanks prior to performing residual stress measurement, but not from the current production tanks, since they had not yet been painted. Paint removal was accomplished in some cases with paint remover. However, this was not a time effective method and was abandoned in favor of using an air-driven wire brush. Small areas about 1/4 inch in diameter were then electropolished at each position about the weldment on which residual stress measurements were to be performed. The portable X-ray equipment was then positioned at each spot, measurements were taken, and the data were recorded.

5.5. Equipment

5.5.1. Electropolishing Equipment. Electropolishing was accomplished with portable equipment manufactured by Struers Inc., Cleveland, OH. (A photograph of the equipment is shown in Figure 5-1.) It consisted of an electrical power supply unit and an electrolyte container with recirculating pump and pencil-shaped polishing probe. The polishing probe was connected to the electrolyte container via plastic tubing. In use, the probe was placed on the object to be electropolished, and the power supply was turned on for a calibrated length of time to achieve the desired depth of polishing, the electrolyte and appropriate voltage being furnished at the probe for this purpose. The polished area measured 0.4 cm². Various electrolyte recipes are available. The recipe for the electrolyte used in this work consisted of 90 ml distilled water, 730 ml ethhanol (ethyl alcohol), 100 ml butylcellosolve, and 78 ml perchloric acid.

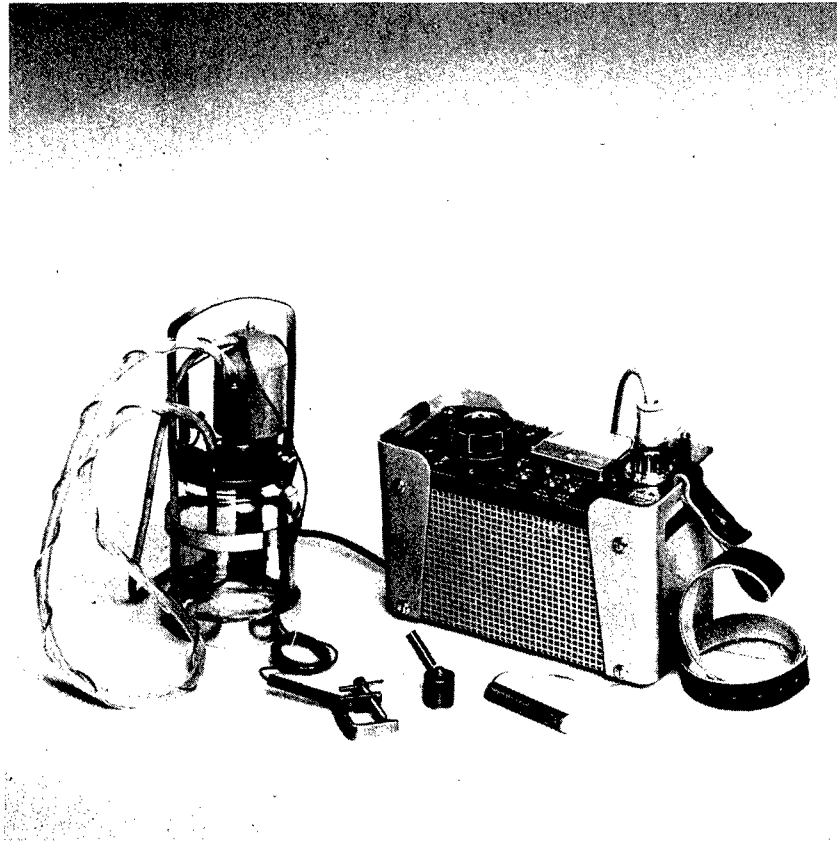


Figure 5-1. Electropolishing Equipment

5.5.2. X-ray Diffraction Equipment. Residual stress measurement was accomplished using a portable X-ray analyzer for residual stress (PARS) unit. The PARS system was developed at Northwestern University for the Office of Naval research. The American Analytical Corp. was contracted to furnish the equipment and to perform the measurements. A feature of this equipment that permits its small size and portability is the use of a position sensitive detector (PSD). When used in conjunction with a multichannel analyzer, it eliminates the bulky goniometer used in conventional X-ray diffractometers used to display diffraction peaks. The electronics supporting the PARS is not portable; it is mounted in an electronic instrument relay rack on casters and consists of an X-ray generator (i.e., high voltage power supply), a video display of the diffraction peak, a multichannel analyzer, a computer, and a printer. The X-ray tube and PSD are assembled into one portable unit and are attached to the supporting electronics via long cable making it possible to move the X-ray tube and PSD without also moving the electronics. A photograph of the X-ray tube and PSD are shown in Figure 5-2. A chromium target X-ray tube and a vanadium filter are used to achieve approximate monochromatic radiation. Operational voltages and current used were 35 kilovolts and 1.7 milliamperes.

5.6. Procedure

5.6.1. Instrument Calibration. Prior to performing residual stress measurements, reference samples of known value were used to check calibration of the PARS unit. At LATP, the contractor's compressive reference sample was used. It was used at the beginning of the first day and at the end of the last day. TACOM's reference samples were used at General Dynamics. One of them was a zero level reference sample, one was a high tensile level reference sample, and the third was a high compressive level reference sample.

5.6.2. Surface Preparation. Surface preparation consisted of paint removal if required, and electropolishing as described in section 5.2.

5.6.3. Instrument Positioning. Due to steep stress gradients in and around the weldments, it is imperative that the X-ray equipment be mounted firmly so as to prevent any movement or vibration during X-ray exposure. This was accomplished by firmly clamping the PARS unit to a drill stand, and positioning this assembly appropriately for each measurement performed.

6.0. RESULTS

The results of this effort are as stated in section 3.0.; the data supporting said results are in the data sheets shown in Figures 6-1 through 6-16. Figures 6-1 through 6-9 are for current production M1 tanks; Figures 6-10 through 6-16 are for preexisting M1 tanks. Tables 6-1 and 6-2 are listings of statistics

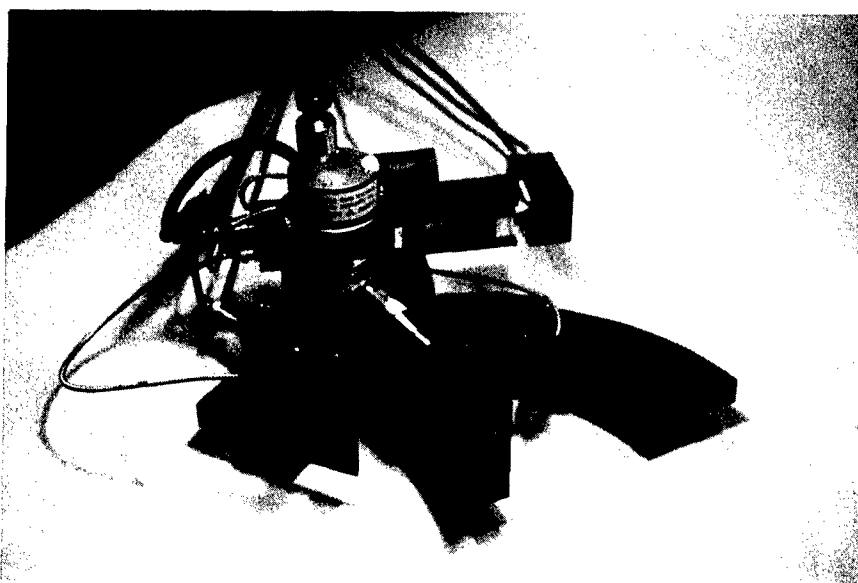
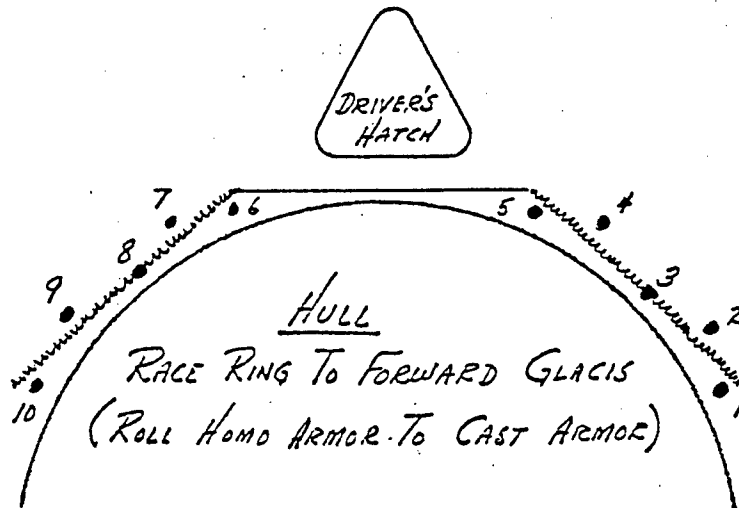


Figure 5-2. Portable X-ray Analyzer for Residual Stress (PARS)

6 AUG 85
 HULL # 3153
 CURRENT PRODUCTION (LATP)

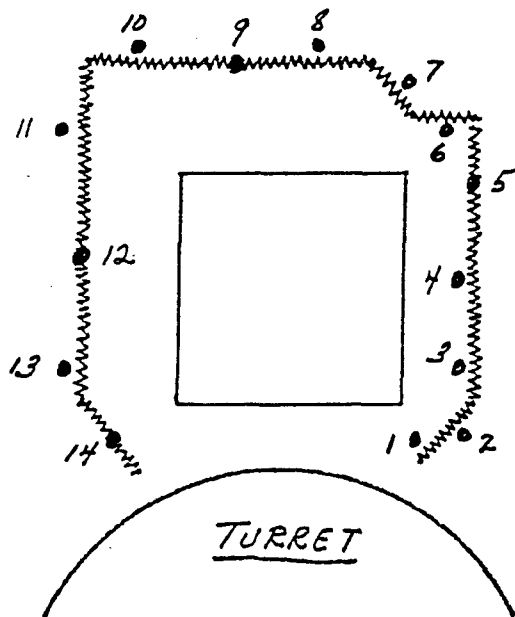


<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
1	-43
2	-9
3	-44
4	-31
5	-55
6	
7	-22
8	-55
9	
10	

Figure 6-1. Data Sheet for Current Production M1 Tanks

derived from data for preexisting and current production M1 tanks. Figures 6-17 and 6-18 are histograms of the data. The listings of statistics and the histograms illustrate that there is no appreciable difference in results obtained on preexisting and current production M1 tanks. All data are expressed in KSI units (i.e., units of 1,000 pounds per square inch.) The accuracy of all data points is estimated to be plus/minus 10 KSI. A negative (sign) value indicates a compressive residual stress; a positive value indicates a tensile residual stress. If not otherwise indicated on the data sheets, all electropolish depths are approximately 4/1000 inch, and residual stress directions are perpendicular to the weld nugget. The weld nugget is represented by a fine saw tooth line in the sketch on each data sheet. Measurement locations are pictured on the data sheets as dots. Some are pictured as being on the weld nugget, representing those measurements taken on the nugget. Other dots are pictured as being to either side of the weld nugget, representing measurements taken near the nugget, but off to one side. The latter measurements were located as close to the weld as possible so as to be positioned in the heat-affected zone of the weldment. An additional measurement was taken at the request of LATP engineers on hull #3029, which had been accidentally dropped in processing. This data point was not included in the data sheets of this report; it was on a weldment other than those depicted in the data sheets. The measurement was taken in the heat-affected zone of the weldment at a point near the point of impact with the floor. The weldment was electropolished and the measurement was taken in the direction perpendicular to the weld nugget. The residual stress level was found to be 70,000 psi compressive. This data point was included in the statistics of Table 6-1, ~~and 6-2,~~ as well as in the histograms of Figure 6-17, ~~and 6-18.~~

6 AUG 85
 TURRET # 3015 (SHOT BLAST)
 CURRENT PRODUCTION (LATP)

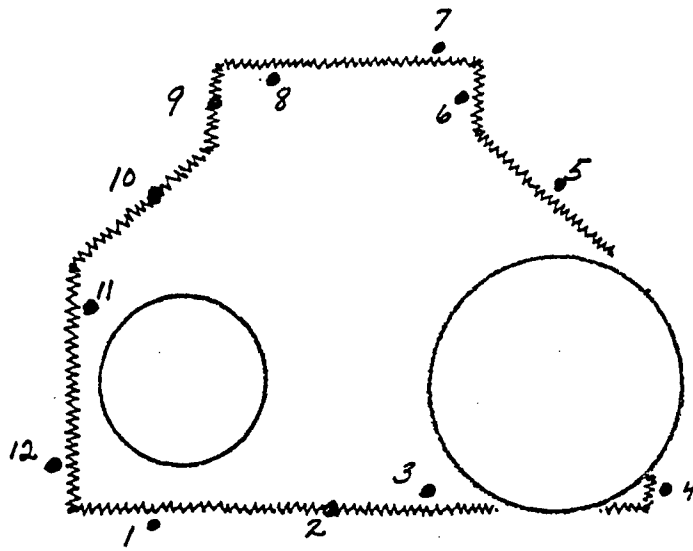


GUNNER PRIMARY SIGHT TO FRONTAL SLOPE PLATE
 (CASTING TO TWO WROUGHT PLATES)

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>	
1	-122	
2	-44	
3	-91	
4	-73	
5	-42	
6	-59	
7	-65	ELECTROPOLISH 4 MILS
7 REPEAT	-65	ELECTROPOLISH 8 MILS
8	-77	
9	-120	
10	-98	WITHOUT ELECTROPOLISH
10 REPEAT	-42	ELECTROPOLISH 4 MILS
11	-103	
12	-22	
13	-64	
14	-69	

Figure 6-2. Data Sheet for Current Production M1 Tanks

6 AUG 85
 TURRET # 3015 (SHOT BLAST)
 CURRENT PRODUCTION (LATP)

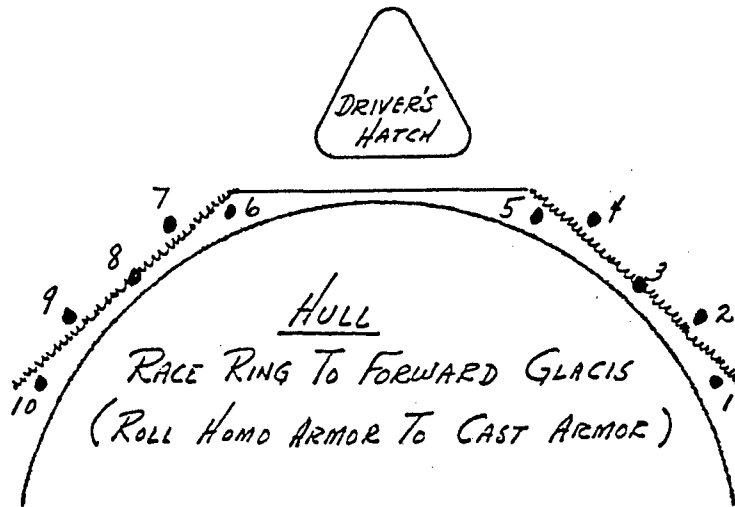


TURRET ROOF PLATE JOINT

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
1	-73
2	-70
3	-86
4	
5	-39
6	-95
7	-100
8	-64
9	-86
10	-90
11	-70
12	-81

Figure 6-3. Data Sheet for Current Production M1 Tanks

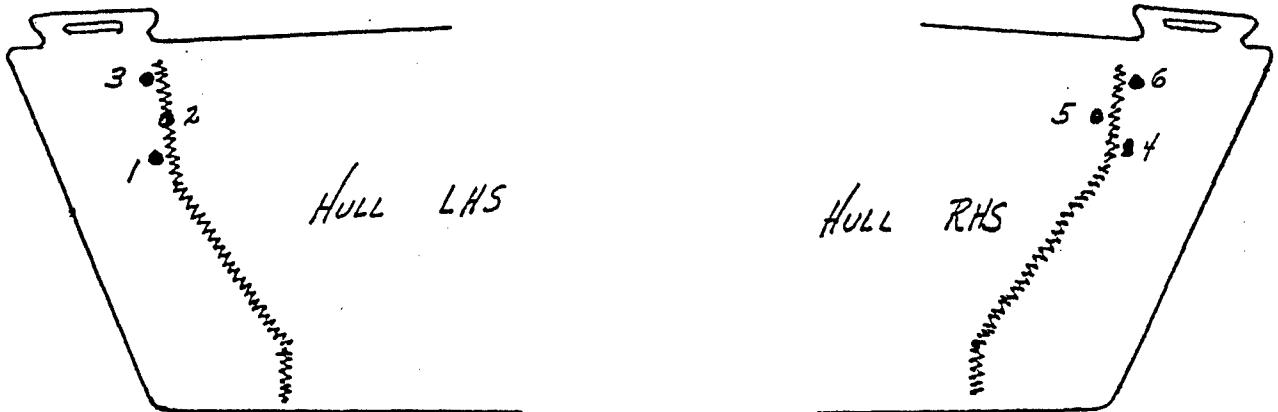
7 AUG 85
 HULL # 3118-1
 CURRENT PRODUCTION (LATP)



<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
1	+ 17
2	- 64
3	- 81
4	- 95
5	+ 47
6	- 21
7	+ 9
8	- 90
9	
10	

Figure 6-4. Data Sheet for Current Production M1 Tanks

7 AUG 85
 HULL # 3118-1
 CURRENT PRODUCTION (LATP)

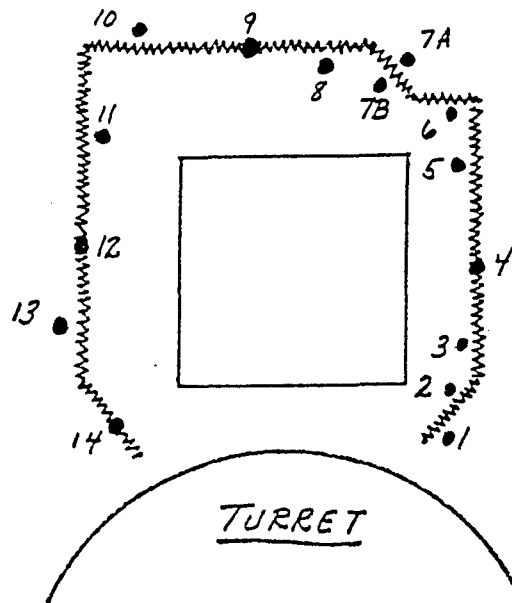


SIDE PLATE TO FRONT PORTION OF HULL SIDE PLATE TO FRONT PORTION OF HULL

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
1	-4
2	-5
3	-53
4	-35
5	-109
6	+38

Figure 6-5. Data Sheet for Current Production M1 Tanks

7 AUG 85
 TURRET # 3018
 CURRENT PRODUCTION (LATP)

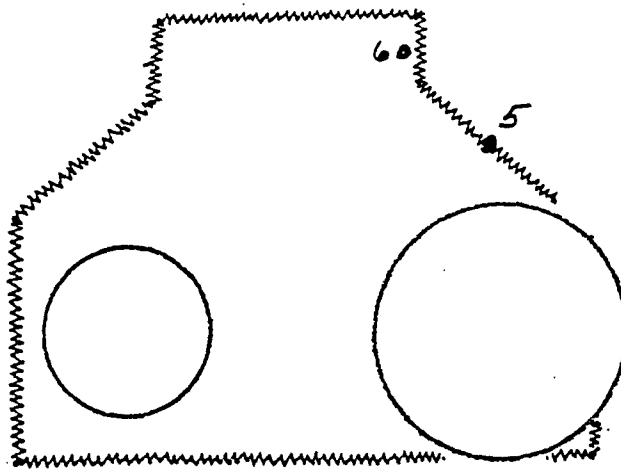


GUNNER PRIMARY SIGHT TO FRONTAL SLOPE PLATE
 (CASTING TO TWO WROUGHT PLATES)

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>	
1	-119	
2		
3	-51	
4	-90	
5	-65	
6	-47	
7A	-74	(-14 PARALLEL TO WELD NUGGET)
7B	-60	(-35 PARALLEL TO WELD NUGGET)
8	-8	
9	-108	
10	-21	
11	-26	
12	-26	
13	-34	
14	-13	

Figure 6-6. Data Sheet for Current Production M1 Tanks

7 AUG 85
 TURRET # 3018
 CURRENT PRODUCTION (LATP)



TURRET ROOF PLATE JOINT

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
5	-27
6	-138

Figure 6-7. Data Sheet for Current Production M1 Tanks

8 AUG 85

HULL # 3029 (SHOT BLAST)

CURRENT PRODUCTION (LATP)

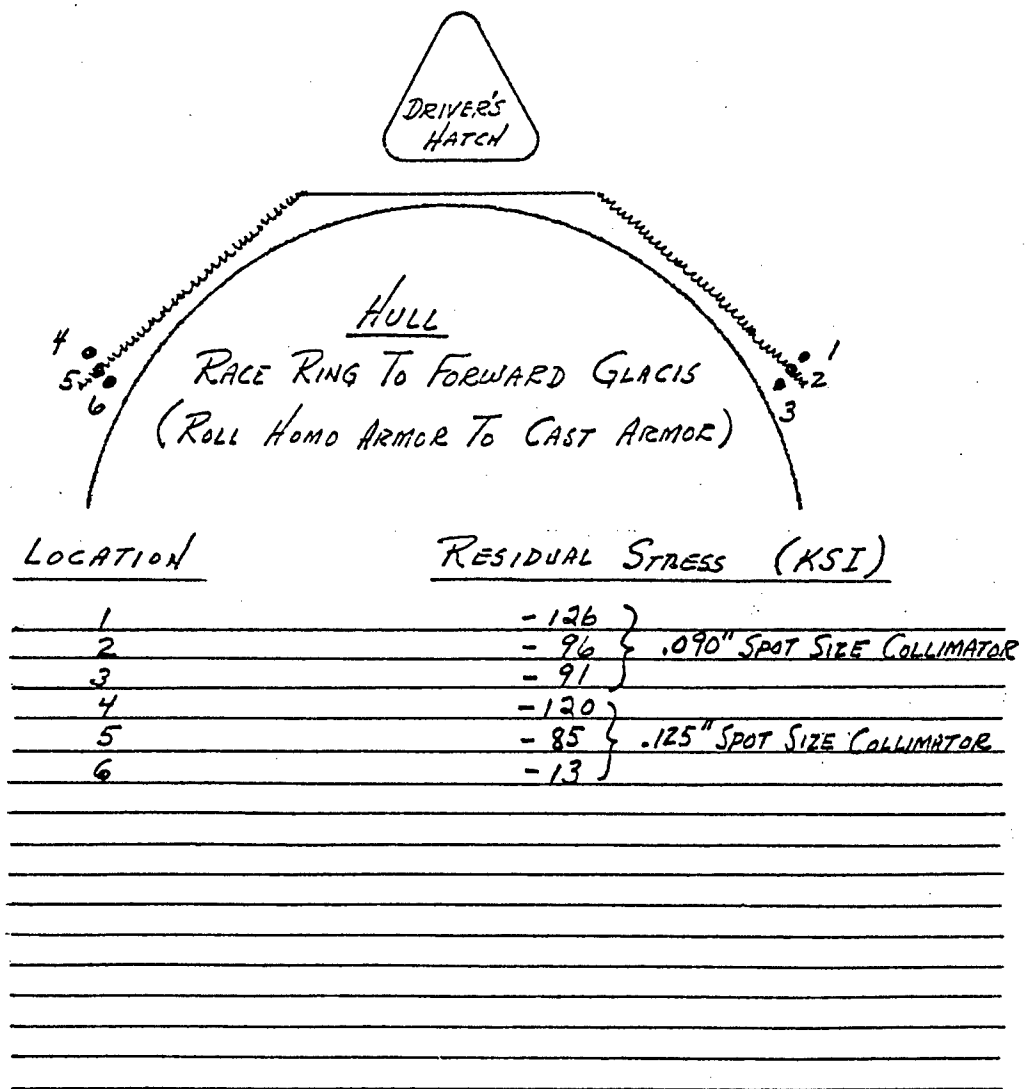
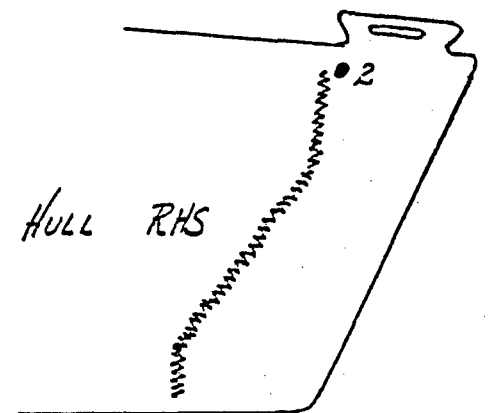
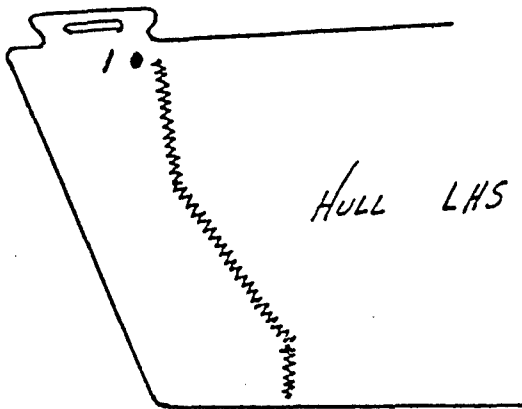


Figure 6-8. Data Sheet for Current Production M1 Tanks

8 AUG 85
HULL # 3029 (SHOT BLAST)
CURRENT PRODUCTION (LATP)



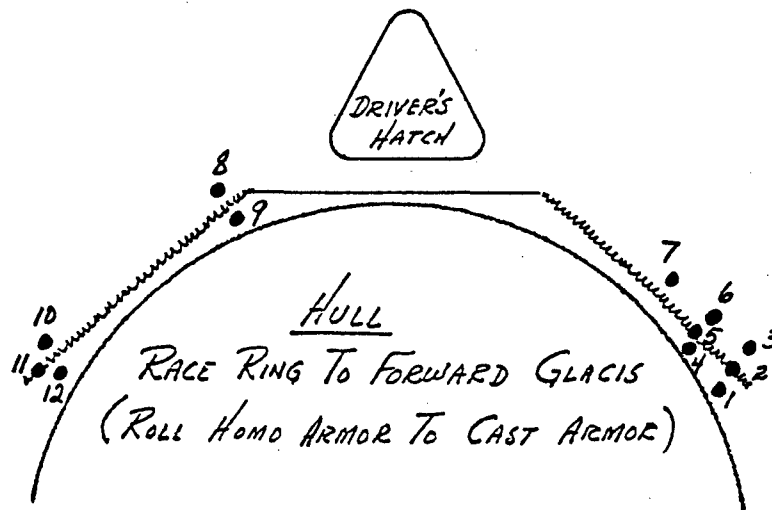
SIDE PLATE
TO FRONT PORTION OF HULL

SIDE PLATE
TO FRONT PORTION OF HULL

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>	
1	-154	} .090" SPOT SIZE COLLIMATOR
2	-60	

Figure 6-9. Data Sheet for Current Production M1 Tanks

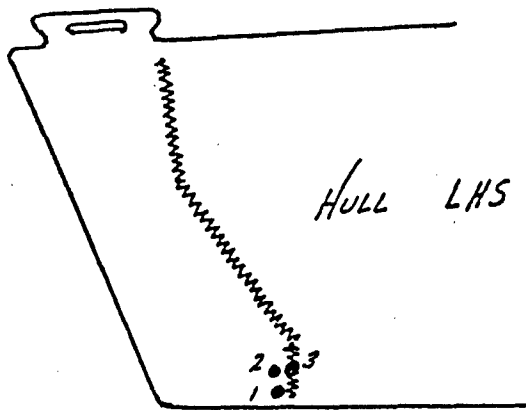
21 AUG 85
 VEHICLE No. L 019
 ODOMETER 1880 KM
 ENGINE HRS 641



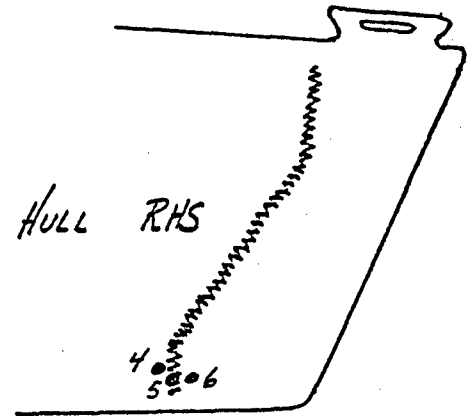
<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
1	-70
2	-30
3	-27
4	+4
5	-78
6	-59
7	-65
8	-78
9	-86
10	-55
11	-95
12	-104

Figure 6-10. Data Sheet for Preexisting M1 Tank Weldments

21 AUG 85
 VEHICLE No. L 019
 ODOMETER 1880 KM
 ENGINE HRS 641



SIDE PLATE
 TO FRONT PORTION OF HULL

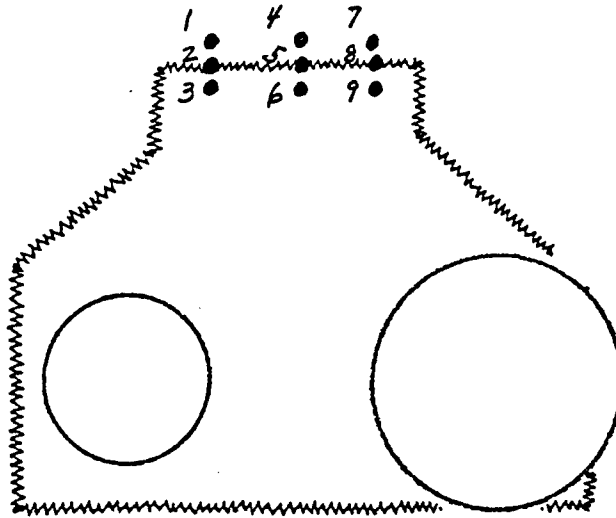


SIDE PLATE
 TO FRONT PORTION OF HULL

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
1	-39
2	-74
3	-21
4	-35
5	-47
6	-10

Figure 6-11. Data Sheet for Preexisting M1 Tank Weldments

21, 22 AUG 85
 VEHICLE L019
 ODOMETER 1880 KM
 ENGINE HRS 641

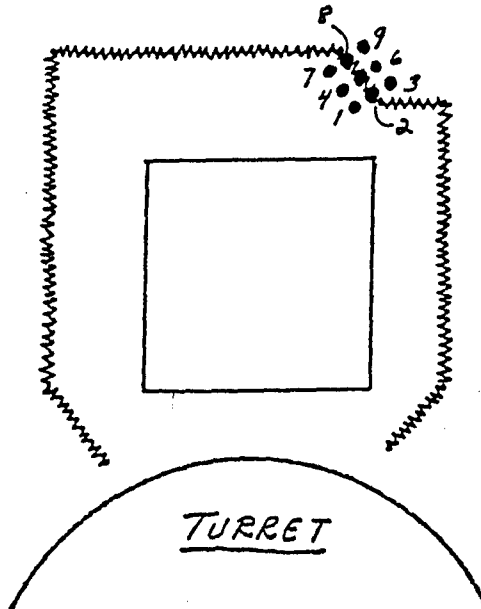


TURRET ROOF PLATE JOINT

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
1	-62
2	-87
3	-124
4	-56
5	-129
6	
7	-81
8	-121
9	-134

Figure 6-12. Data Sheet for Preexisting M1 Tank Weldments

21 AUG 85
 VEHICLE No L 019
 ODDMETER 1880 KM
 ENGINE HRS. 641

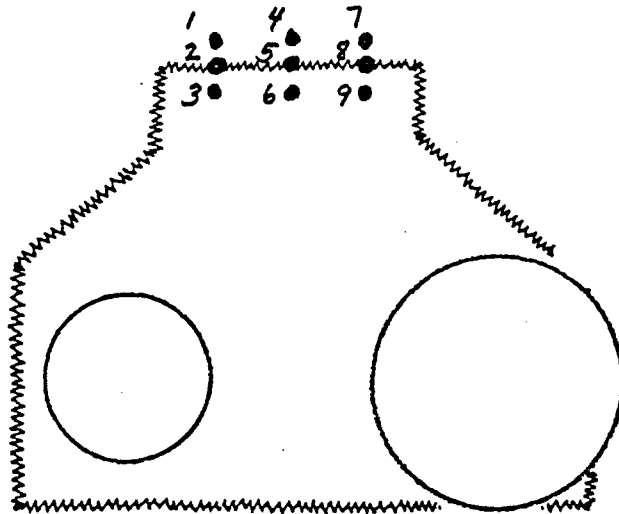


GUNNER PRIMARY SIGHT TO FRONTAL SLOPE PLATE
 (CASTING TO TWO WROUGHT PLATES)

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>	
	<u>0.010" ELECTROPOLISH</u>	<u>0.020" ELECTROPOLISH</u>
1	-99	
2	-113	
3	-100	
4	-102	-70
5	-74	
6	-56	
7	-122	
8	-77	
9	-82	

Figure 6-13. Data Sheet for Preexisting M1 Tank Weldments

22 AUG 85
 VEHICLE L02
 ODOMETER 6285.2 KM
 ENGINE HOURS 840

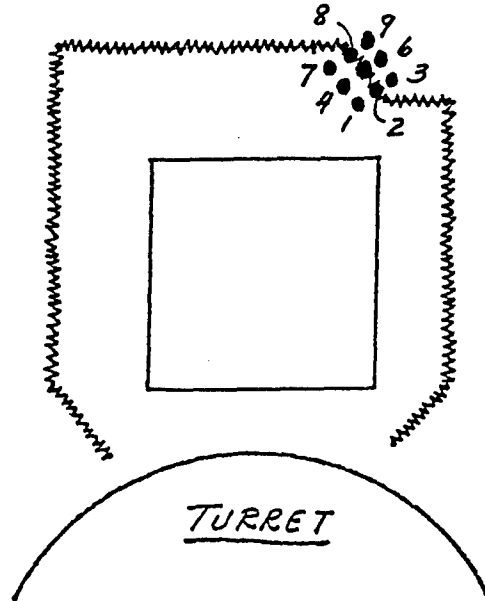


TURRET ROOF PLATE JOINT

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
1	-94
2	-74
3	-87 (-73 PARALLEL TO WELD NUGGET)
4	-43
5	-107
6	-52
7	-61
8	-117
9	-56

Figure 6-14. Data Sheet for Preexisting M1 Tank Weldments

22 AUG 85
 VEHICLE NO. L 02
 ODOMETER 6285.3 KM
 ENGINE HRS. 840

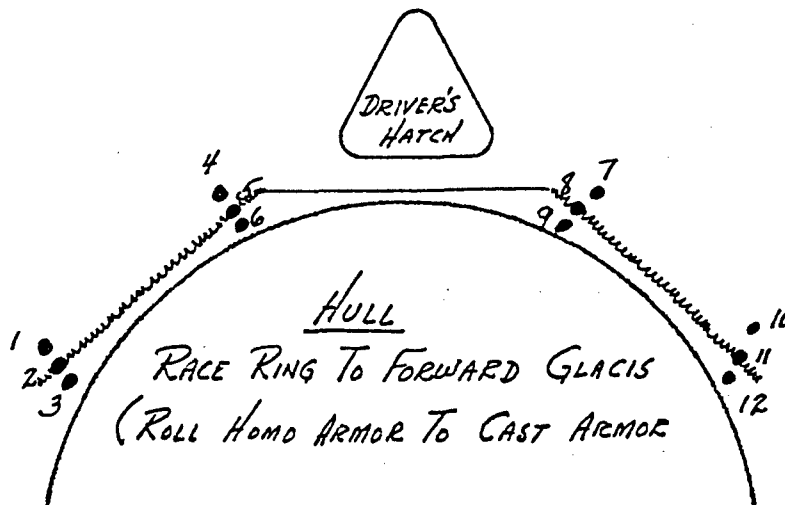


GUNNER PRIMARY SIGHT TO FRONTAL SLOPE PLATE
 (CASTING TO TWO WROUGHT PLATES)

<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
1	-53
2	-111
3	-55
4	-109
5	-73
6	-96
7	-65
8	-39
9	-86

Figure 6-15. Data Sheet for Preexisting M1 Tank Weldments

22 AUG 85
 VEHICLE NO. L 01
 ODOMETER 2506.8 KM
 ENGINE HRS. 980



<u>LOCATION</u>	<u>RESIDUAL STRESS (KSI)</u>
1	-78
2	-77
3	-108
4	-54
5	-81
6	-73
7	-81
8	-65
9	+13
10	-121
11	-60
12	-99

Figure 6-16. Data Sheet for Preexisting M1 Tank Weldments

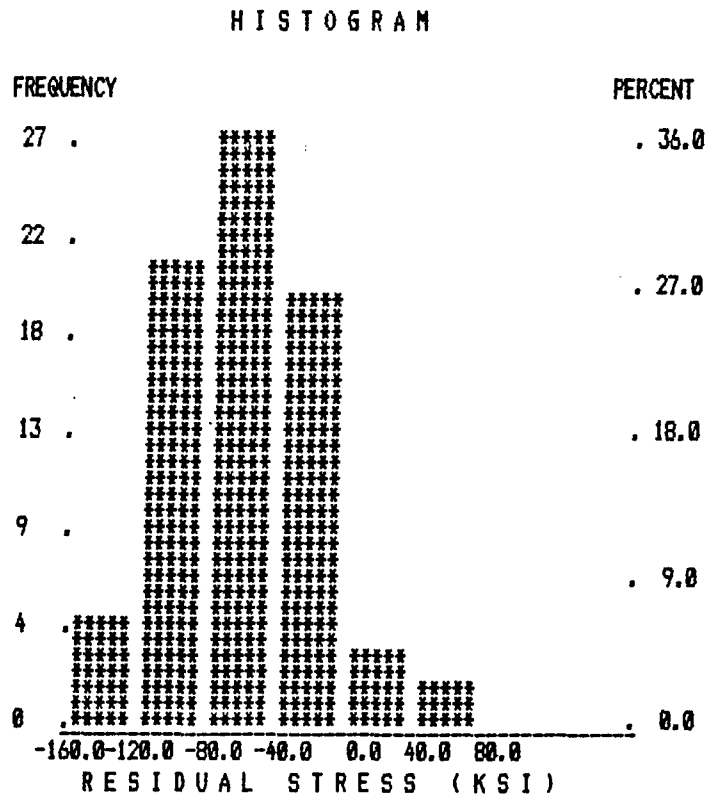


Figure 6-17. Histogram for Data from Current Production M1 Tank Weldments

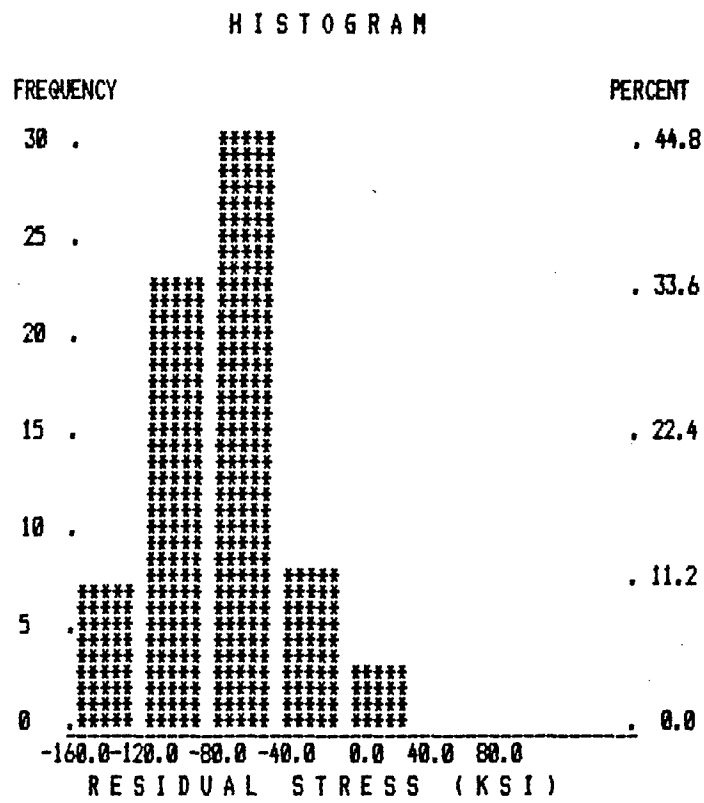


Figure 6-18. Histogram for Data from Preexisting M1 Tank Weldments

Table 6-1. Statistical Data: Residual Stress, Current Production M1 Tank Weldments

Statistic	Value
N (number of readings)	75
Mean	-59.81 KSI
Std. Dev.	40.27 KSI
Skewness	0.205
Kurtosis	2.837

Table 6-2. Statistical Data: Residual Stress, Preexisting M1 Tank Weldments

Statistic	Value
N (number of readings)	67
Mean	-74.52 KSI
Std. Dev.	31.21 KSI
Skewness	0.408
Kurtosis	3.081

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- 3 Catalano, S.B., "Establishment of Rapid X-Ray Diffraction Inspection Techniques for Residual Stresses," TACOM Technical Report No. 12173 (1977)
- 4 Cullity, B.D., "Elements of X-Ray Diffraction," Addison-Wesley Publishing Company, Reading, Mass. (1957)
- 5 Society of Automotive Engineers, "The Measurement of Stress by X-Ray - TR-182," New York, NY (1960)

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