National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

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SPECIFICATION: FUSION WELDING TITANIUM AND TITANIUM ALLOYS

Prepared by:

Materials and Processes Laboratory
Science and Engineering

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GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

FUSION WELDING TITANIUM AND TITANIUM ALLOYS

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GEORGE C. MARSHALL SPACE FLIGHT CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

HUNTSVILLE, ALABAMA

SPECIFICATION

WELDING TITANIUM AND TITANIUM ALLOYS

This specification has been approved by the George C. Marshall Space Flight Center (MSFC) and is available for use by MSFC and associated contractors.

1. Scope

1.1 Scope - This specification covers the engineering and quality control requirements for manual and mechanized fusion welding of titanium alloys for flight and ground support applications.

1.2 Classifications

1.2.1 Fusion Welding Processes:

1.2.1.1 Gas Tungsten Arc Welding (GTAW)

1.2.1.2 Gas Metal Arc Welding (GMAW)

1.2.1.3 Plasma Arc Welding (PAW)

1.2.1.4 Electron Beam Welding (EBW)

1.2.2 Materials - The materials covered in this specification are titanium and titanium alloys.

1.2.3 Weld Classes - Welding performed under this specification shall be classified in accordance with the service of the weldments as follows:

1.2.3.1 Class I welds shall meet the highest quality requirements of this specification and the strength requirements specified by Engineering Design.

1.2.3.2 Class II welds shall meet the quality requirements of this specification and the strength requirements specified by Engineering Design. A Class II weld shall be construed as capable of sustaining a tensile load 80% of a Class I Fusion Weld.

1.2.3.3 Class III welds are non-critical, non-flight with no specified strength level but which meet the quality requirements of 3.11.2

2. APPLICABLE DOCUMENTS

2.1 The following documents form a part of this specification to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or requests for proposals shall apply. When requirements of this specification and requirements of any applicable document conflict, the requirements of this specification shall take precedence.

SPECIFICATIONS, STANDARDS AND OTHER PUBLICATIONS

MIL-STD-1595 - Aerospace Welder Performance Qualification

MIL-A-18455 - Argon, Technical

MIL-P-27407 - Helium

MIL-STD-453 - Inspection - Radiographic

MIL-STD-410 - NDT Personnel Qualification and Certification

NAS 1514 - Radiographic Standard for Classification of Fusion Weld Discontinuities

George C. Marshall Space Flight Center

MSFC-STD-506 Material & Process Control

MSFC-STD-366 Penetrant Inspection Method

MSFC-STD-655 Weld Filler Metal, Control of

MSFC-SPEC-522A Design Criteria for Controlling S.C. Cracking

MSFC-SPEC-469 Heat Treating, Specification for

Copies of specifications, standards, procedures, drawings, and publications required by contractors in connection with specific procurement functions shall be obtained from the procuring agency or as directed by the contracting officer.

American Welding Society

AWS A2.4 Symbols for Welding and Non-Destructive Testing

AWS A3.0 Welding Terms and Definitions

AWS A5.12 Tungsten Arc Welding Electrodes

AWS A5.16 Titanium and Titanium Alloy Bare Welding Rods and Electrodes

(Application for copies should be addressed to the American Welding Society, 2501 N.W. 7th Street, Miami, FL 33125).

American Society for Testing and Materials

ASTM-E-8 Methods of Tension Testing of Metallic Materials

(Application for copies should be addressed to American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103).

American Society of Mechanical Engineers

Boiler and Pressure Vessel Code, SEC IX-ASME, 1974 Edition

(Copies of this code may be obtained from the procuring activity or as directed by the contracting officer).

3. REQUIREMENTS

3.1 Welder or Welding Operator Qualification - Each fabricator or contractor shall qualify by performance testing each welder, or welding operator, for each welding process to be used by that welder in production welding, in accordance with an approved welding procedure specification. Details which are essential variables of the welding specification, shall be followed in making the performance qualification test. Welders or welding operators shall be qualified in accordance with requirements of MIL-STD-1595.

3.2 Record of Proficiency - Ref. Record Sheet 1

3.3 Welding Procedure Specification - All welds shall be made in accordance with a qualified welding procedure specification (WPS), Ref. Record Sheet 2 and documented with a procedure qualification record - Ref. Record Sheets 3 and 3A.

3.3.1 Welding Procedure Specification - Qualification - Prior to welding the first production part, a detailed written procedure shall be established for each weld (or group of similar welds) of each component. A qualification weld shall be made to simulate the production part with respect to section thickness, alloy, heat treatment, joint preparation, welding position and progression, pre-weld cleaning and fit-up and other essential and non-essential variables relevant to the welding process and procedure. The qualification weld shall be made in either the actual production fixture or in a test fixture simulating the production fixture using the production welding equipment. The data required in the certified weld procedure is shown in Table I. Test piece(s) shall be of sufficient length and width to provide the required test specimens.

3.3.1.1 The qualification weld shall be subjected to the processes affecting mechanical properties to which the production part will be subjected, such as reinforcement removal, mechanical deformation and post weld thermal treatment required to meet design limits.

3.3.1.2 The qualification weld shall be visually and nondestructively examined for acceptance as specified in 3.11.2. In addition, a representative sample of the completed weldment shall be analyzed for H_2, O_2, and N_2 content, using the Vacuum Fusion Analysis technique, to assure conformance to the purity requirements. The interstitial level of the completed weld shall not exceed the Worst Case Maximum level permissible in the procurement specification for the base materials being welded.

3.3.1.3 Tensile Tests - A minimum of four specimens shall be tested per ASTM-E-8 for each qualification weld. Tensile specimens shall be tested to destruction at room temperature. For rectangular specimens, percent elongation in 1.0 inch and 2.0 inch, and ultimate tensile load shall be recorded. Percent elongation for round specimens shall be measured across a 4D gauge length. Weld strength shall equal or exceed engineering documentation requirements.

3.3.1.4 Guided Bend Tests - Bend specimens shall be selected, prepared and tested in accordance with MIL-STD-1595

3.3.1.5 Metallographic Sections - The welded joint for each type specified (butt and fillet) shall be sectioned transverse to the weld direction and the surface of the section shall be ground and polished to suitable surface finish. The polished section shall be examined visually and at a magnification of 10 diameters for fusion characteristics and weld defects. Any crack is unacceptable. The section shall then be lightly etched to reveal micro-structure and reexamined at a higher magnification. The weld cross section shall contain no titanium hydrides (TiH_2) or alpha case. These two detrimental phenomena are indications of the hydrogen content exceeding the solubility limit and an oxygen-enriched alpha-stabilized surface resulting from air contamination at elevated temperatures, respectively.

The weld cross section shall be examined for the following characteristics in accordance with Para's 4.3 and 4.5.

(a) Overall fusion of the weld, root penetration, burn-through and blowholes.
(b) Convexity, concavity and size of bead or fillet.
(c) Undercutting and overlapping.
(d) Inclusions or voids.
(e) Cracks

3.3.1.6 Special Tests - Special tests stipulated by engineering design shall be conducted as supportive evidence of meeting design requirements. Such tests may include fatigue, hardness, impact, etc.

3.3.1.7 Welding Procedure Qualification Record - The qualification welding schedule, including weld evaluation results shall be prepared and retained as a permanent record. One copy shall be displayed at the welding station (Ref. Record Sheets 2, 3, and 3A).

3.4 Materials

3.4.1 Base Metal - Unless otherwise specified or approved by the procuring agency the base metals shall be those shown in Table II and shall meet the requirements of MSFC-SPEC-522A and MSFC-STD-506.

3.4.1.1 Base metal for qualification welding tests shall be identified by heat or lot number, type and condition, and shall maintain identification through all evaluation processes.

3.4.2 Filler Metals - Unless specified by engineering drawing, contract or by a detailed specification, filler metals shall be selected from the appropriate specification listed in Para. 2.1 and in Table II. Filler metals not covered by this specification shall be approved by the procuring agency prior to use. Commercially pure Ti wire is not to be used for joining Ti-6Al-4V parent material. All filler wire to be controlled per MSFC-STD-655.

3.4.3 Shielding Gas - Welding grade argon (MIL-A-18455) and Helium (MIL-P-27407) or a combination of these gases shall be used for Inert Gas Welding. Any other gases or combinations thereof shall be approved by the procuring agency prior to use.

3.5 Welding Equipment - Welding equipment shall be capable of producing acceptable welds when operated by a qualified operator in accordance with a qualified welding procedure specification (WPS). Welding equipment shall be initially calibrated, and then periodically each month, and records kept of calibration values and dates for such welding equipment.

3.6 Tooling - Tooling and fixtures used in the welding operation shall be constructed of materials that do not affect the welding arc, are not detrimental to weld quality, and will not affect properties of the base material via surface to surface contact.

3.7 Marking and Identification of Welds - Each welder or welding operator shall be assigned an identifying symbol to identify all welds requiring documentation. The identification symbol shall be applied to production documents authorizing the welding operation in such a manner that it is traceable to the weld. Identification and marking of welds shall be accomplished using halogen free materials or techniques that will not adversely affect the properties of the base material or weldment.

3.8 Safety - All hazardous materials and processes required in compliance with provisions of this specification are subject to applicable Federal, State, and Local Safety Codes, standards and regulations. Appropriate personal protection shall be used in all hazardous processes.

3.9 Pre-Weld Conditions

3.9.1 Cleaning - Joints to be welded shall be cleaned and degreased prior to welding for a distance of at least one inch from the edge. Cleaning may be achieved using a clean draw file which has been used only on titanium or with silicon carbide garnet paper, followed by acetone wipe using lint free white cloth. Metal brushing, steel wool, sandpaper and halogenated solvents are not permitted. Jigs, clamps and fixtures contacting the titanium material shall be cleaned prior to use.

3.9.2 Weld Chamber - All welding (other than Electron Beam), including tack welding, shall be performed in an inert gas welding chamber. The chamber shall have continuous atmosphere monitoring of moisture and oxygen. The entire chamber or attached integral ante-chamber must be capable of being evacuated and back filled with inert gas. When in use, inert atmosphere welding chambers shall be cleaned

once a week to reduce the possibility of weld contamination from foreign matter within the chamber. Note: Water cooled welding torches are not recommended due to potential source of leaks from the torch.

3.9.3 Weld Atmosphere - The atmosphere shall be freely accessible to all portions of the joint. Auxiliary root purging shall be used during welding of tubes and other components having stagnant spaces. The effluent weld atmosphere shall be continuously monitored for moisture and oxygen content. Dewpont shall be -60°F or drier, and oxygen content shall not exceed 50 ppm. Atmospheric purity shall be verified by fillerless fusing a commercially pure (CP) titanium strip, .090" or less thick, which has been properly cleaned. A fusion zone and heat affected zone with a silver or light straw color only is acceptable. (Weld discoloration in increasing order of contamination is bright silver, light straw, dark straw, light blue, dark blue, gray blue, gray and white loose powder.) No tacking or welding shall be performed on the hardware until such acceptance color has been obtained.

3.9.4 Formed Joint Edges - Severely formed titanium and titanium alloy parts which could experience weld cracking due to forming stresses shall be stress relieved prior to welding. Stress relief shall be in accordance with MSFC-SPEC-469.

3.9.5 Joints Requiring Full Penetration - Any groove joint requiring full joint penetration may be prepared and welded from either the face side, root side, or both sides. Techniques such as partial penetration pass welds from two sides, which have the potential for building in undetectable flaws, shall not be used in any design or fracture critical application. The preparation geometry may be varied from the groove symbol call out to accommodate ease in welding except when the geometry is detailed on the drawing. In the event the groove geometry varies from the groove symbol call out, the geometry variation shall be approved by the procuring agency prior to welding.

3.9.6 Joints Requiring Partial Penetration - Any groove joint requiring partial penetration shall be prepared only from the side designated by the weld symbol. The preparation geometry is detailed on the part drawing.

3.9.7 Inspection - Prior to welding of each production part, a pre-weld inspection shall be performed in accordance with Para 4.2.

3.10 Production Welding

3.10.1 Welding Procedure - The qualified welding schedule, per paragraph 3.3.1.7, shall be used for tacking and welding on production parts.

3.10.1.1 The filler metal used for tacking shall be the same filler metal alloy as specified for the weld.

3.10.1.2 The length and size of tack welds shall be limited to a size that will be melted by the subsequent weld pass or layer.

3.10.1.3 Weld Start and Run-Off Tabs - Weld start and run-off tabs, when used, shall be composed of the same alloy as the detailed parts, and shall be welded with the same filler metal specified on the drawing.

3.10.1.4 Schedule Departure - Departure from the qualified welding schedule during production welding shall require withholding the part for material review board disposition. The cause for departure shall be determined and corrective action taken prior to further production welding.

3.10.1.5 Welding Equipment -A welding equipment readiness check shall be made immediately prior to a production weld to verify the equipment is operating properly and in accordance with the qualified schedule. The atmospheric purity verification test (par 3.9.3) may suffice for all but the wire feed rate.

3.10.1.6 Rewelding - Inprocess repair welding shall be limited to two rewelds provided that the repair welding parameters and procedures are specified in a qualified repair welding schedule, and the repair is contained within the original weld zone. Complete records of the repair welding operation, including identification of the repaired weldments, type of defect, and location of the repair weld shall be retained in permanent records for Class I and Class II welds.

Repair welding shall not be permitted when:

(a) The weldment has been machine finished, or subsequently heat treated to increase strength.

(b) The wrong filler metal has been used.

(c) The weldment is discolored to a rejectable level (para 3.9.3).

(d) A weldment has been contaminated by fusion to a dissimilar weld fixture.

3.10.1.7 Defects in Class III welds may be repaired at the discretion of the contractor's welding engineer.

3.11 Post-weld operations

3.11.1 Inspection - Each completed weldment, and the base metal for 12.5 mm (1/2 in.) on either side of the weld edge, shall be inspected to assure compliance with the requirements of 3.11.2, and as dictated by the class of weld, Table III.

3.11.1.1 Nondestructive testing procedures to be employed in inspection for weldment internal and surface quality requirements shall be qualified/validated as being capable of detecting the weldment quality criteria prescribed, prior to inspection of the first production weld. The documentation proof of capability shall be retained as a permanent record. See Para 4.7.

3.11.2 General Workmanship Requirements - When employing visual inspection, weld deposits, buildup, and root penetration shall display a uniform appearance. The edge of the weld deposit shall blend into the base metal without unfused overlaps or undercut. The face and root sides shall be free of surface cracks, crater cracks, and other defects open to the surface. Except in the case of fillet welds, both the crown and the penetration of the weldment shall be convex. The deposit shall be free of open voids or unfused overlapping folds.

3.11.3 Weldment Straightening - Welds and adjacent base metal which have been deformed by the welding operation may be straightened; however, prior to implementation the contractor shall verify by destructive testing and metallurgical evaluation that the process used for straightening shall not degrade the

weld and surrounding material below specified design requirements.

3.11.3.1 Following weldment straightening, the weld and adjacent base metal shall be inspected in accordance with 3.11.2. Weldments in which defects have been revealed by such operations shall not be acceptable.

3.11.4 Weld Reinforcement Removal - Weld reinforcement may be removed as required, so long as the design thickness of weld has not been reduced below the minimum design requirements.

3.11.5 Weldment Heat Treatment - When post weld heat treatment is required, welds shall be heat treated in accordance with MSFC-SPEC-469, and shall be inspected for surface quality requirements of paragraph 3.11.2 and the requirements of MSFC-SPEC-469 .

4. QUALITY ASSURANCE REQUIREMENTS

4.1 The supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own or any other inspection facilities and services acceptable to and approved by the procuring agency. A complete set of inspection and test records shall be kept and upon request, made available to the procuring agency, or its designated representative. The procuring agency or its designated representative reserves the right to perform any or all of the reviews/inspections set forth in this specification to ensure that the end item conforms to the prescribed requirements.

4.2 Pre-weld and Weld Inspection

4.2.1 Documentation relative to the production weld shall be reviewed/inspected for conformance with para 3.

4.2.2 Filler metal(s) shall be examined for conformance with para 3.4.2, the welding procedure specification, and MSFC-STD-655.

4.2.3 Inert gas shielding shall be examined for conformance with para 3.4.3 and welding procedure specification

4.2.4 Welding equipment shall be inspected for conformance with para 3.5.

4.2.5 Tooling shall be inspected for conformance with para 3.6.

4.3 External Weldment Quality Requirements - Classes I and II fusion welds shall meet the following external quality requirements: The external weld quality shall be in accordance with the standards established in this section, except that provision is made for establishing acceptance standards for specific part conditions which can be defined and approved by the discretion of the procuring agency. The standards shall apply to as-welded surfaces and post-weld heat treated and machined or ground surfaces, on both face and root sides of welds which are accessible for inspection from both sides, and to the face side of partial penetration welds, and welds inaccessible for root inspection. Except as noted below, Class I and Class II weld surfaces which are machined or ground shall be etched and dried prior to penetrant inspection.

4.3.1 Cracks - Cracks in the weld metal or adjacent metal shall not be acceptable.

4.3.2 Undercut, Underfill and Suckback - Undercut, lack of fill or suckback (Figure 1) shall be unacceptable in any weld where it occurs as a sharp discontinuity or where minimum material thickness is below design specification.

4.3.3 Weld Spatter and Arc Strikes - All weld spatter and arc strikes shall be removed from accessible surfaces in a manner to produce a surface finish which will conform to engineering drawing requirements.

4.3.4 Surface Roughness - Surface finish of welds, after reinforcement removal for any reason, shall not exceed 125 microinches.

4.3.5 Surface Coloration - The weld deposit and heat affected zone shall be a light straw or bright silver color.

4.3.6 Joint Offset - The post weld offset between two sheets or plates of a butt welded joint shall not exceed 20% of the thinnest member or 1.50 mm (.060") whichever is least for material thicknesses of 12.5 mm (.500") or less. For material thicknesses greater than 12.5 mm (.500"), offset shall not exceed 3.0 mm (0.120") or 10% of the material thickness (T), whichever is least. Offset shall be measured at a distance 0.13 inch from the edge of the weld fusion zone as shown in Figure 2(a). Measurements shall be taken at the rootside of the weld when accessible for such measurements. For curved weldments, offset shall be measured along the approximate radius of curvature of each joint member as shown in Figures 2(b) and 2(c).

4.3.7 Peaking - Peaking of the weld bead and adjacent base metal shall not exceed a total angle of 5 degrees as shown in Figure 3. When a weld will be subsequently intersected by another weld, peaking shall not exceed a total included angle of 2 degrees for the 15.2 cm (6 in.) of the weld adjacent to the weld intersection. A standard template or other device having specified reference points shall be used for determination of peaking.

NOTE: The combined effect of offset and peaking on the efficiency of the weld joint are so related that one can be increased if the other is decreased. This condition can be tolerated if test data can substantiate that the combined stress effect still meets the design allowables.

The maximum permissible peaking and offset allowed in this specification is voided if dimensional variations are beyond acceptable limits for proper assembly tolerances as specified on engineering drawings.

4.3.7.1 Weld Penetration - Weld penetration requirements shall apply to 100% of the lineal length of weld, and conform to the type and class of weld designated on the engineering design drawings.

4.3.8 Weld Size - Weld size requirements for butt welds and fillet welds shall apply to the entire length of weld.

4.3.8.1 Butt Welds - The dimensions of butt welds shall correspond to the reinforcement and size requirements of the engineering design drawing, and will relate to the type of welding process being used. Figure 4 and Table IV indicates the dimensions considered critical to a butt type weld which will be specified by applicable design drawing and/or manufacturer's specification.

4.3.8.2 Fillet Welds - The dimensions of right angle, acute angle and obtuse angle fillet welds shall correspond to the engineering design drawing.

4.3.8.2.1 The minimum acceptable fillet size shall be that specified by engineering drawing. Figures 5A, 5B and 5C outline weld profiles for right, acute and obtuse angle fillet welds. Figure 5D quantifies maximum and minimum dimensions allowable for fillet weld leg lengths.

4.3.8.2.2 The minimum acceptable actual throat shall equal or exceed the theoretical throat; however, fillet welds with acute angle joints of 65 degrees or less may have an unfused root not more than 0.125 inch wide (See Figure 6A).

4.3.8.2.3 A maximum of 0.032 inch depth of drop-through on both legs is permissible on all material thicknesses. The width of drop-through shall not exceed the fillet leg length (See Figure 6B). Removal of excess drop-through is permitted.

4.3.8.2.4 Fillet welds terminating at corners, with unwelded joints, shall have the fillet continued around the corner into the unwelded joint a minimum of 0.12 inch; and a maximum of 0.50 inch.

4.3.9 Machined Welds - Discontinuities of a weld exposed by machining shall be evaluated as surface discontinuties.

4.3.10 Imperfect Fusion - Incomplete penetration, laps or folds that tightly overlap adjacent material shall be interpreted as cracks and are unacceptable.

4.3.11 Surface Discontinuities - Acceptance requirements for surface discontinuties shall be in accordance with NAS 1514, Class I, II and III.

4.3.11.1 Individual Discontinuity - The size of an individual discontinuity, either round or elongated, is determined by the diameter (in inches) of the smallest circle which would contain the entire discontinuity.

4.3.11.2 Scattered Discontinuity - An indication is considered a scattered discontinuity if it is separated from all adjacent indications by a distance equal to or greater than the largest discontinuity size permitted per paragraph 4.3.11.4 and paragraph 4.3.11.5.

4.3.11.3 Cluster Discontinuity - Two or more successive indications which do not meet the requirements for scattered discontinuity must be evaluated to the requirements of a cluster discontinuity. A cluster discontinuity is considered as two or more indications which can be contained within a circle whose diameter is equal to or less than the maximum discontinuity size permitted in paragraph 4.3.11.4 and paragraph 4.3.11.5.

4.3.11.4 Maximum Discontinuity Size - The maximum allowable discontinuity size for butt welds shall be 20 percent of design weld thickness or 0.020 inch, whichever is smallest for thicknesses up to 0.133 inch, the maximum allowable discontinuity size of butt welds greater than 0.133 inch shall be 15 percent of design weld thickness or 0.060 inch, whichever is smallest. The maximum allowable discontinuity size for fillet welds shall be 15 percent of the minimum leg design size or 0.045 inch, whichever is smallest. Discontinuity size of a particular indication shall be determined as the diameter (in inches) of the smallest circle which could contain the entire discontinuity.

4.3.11.5 Discontinuity Summation - Scattered discontinuities and cluster discontinuities not exceeding limitations as stated herein shall be evaluated for accumulative area in accordance to 0.03T square inches maximum allowable discontinuity area for Class I welds and 0.06 T square inches maximum allowable discontinuity area for Class II welds per each six consecutive lineal inches of weld, where T = design weld thickness for butt welds
T = Minimum leg design size for fillet welds
In addition to the area requirement, the welds shall also conform to the following:

a. There shall be no more than 12 discontinuities (a cluster counts as one discontinuity) in any lineal inch of weld.

b. There shall be no more than 50 percent of the allowable discontinuity area in any lineal inch of weld within the six consecutive lineal inches of weld.

4.4 Repair Welding

4.4.1 Two repair welding operations may be permitted to correct any condition listed below provided that the repair welding parameters and procedures are specified in a qualified repair welding schedule, and the repair is contained within the original weld zone. Complete records of the repair welding operation including identification of the repaired weldment, type of defect, and location of the repair weld shall be retained in permanent records.

(a) Undercut
(b) Lack-of-fill
(c) Suck-back
(d) Incomplete penetration
(e) Off-center weld nugget
(f) Oxides and porosity exposed to the surface in excess of National Aerospace Standard 1514 limits, Section 3.13.15.

4.4.2 Any further weld repair attempts must be authorized by the Material Review Board.

4.4.3 Any weldment repair area shall be reinspected in accordance with Para's 3.11.1, 4.3 and 4.5.

4.5 Internal Quality Requirements - The internal weld quality for Class I and Class II welds shall apply to the applicable dimensions of the finished part and shall be in accordance with the standards established in this section. Weld areas that do not meet these requirements shall be cause for rejection.

4.5.1 Cracks - Cracks of any kind in the weld metal or adjacent parent metal shall not be acceptable. Inclusions or porosity with sharp crevices or tails shall be evaluated as cracks. The line at the root of fillet welds shall not be considered to be a crack.

4.5.2 Inclusions - Inclusions (including tungsten) without sharp crevices shall be evaluated as porosity.

4.5.3 Incomplete Penetration/Imperfect Fusion - Incomplete penetration, lack of fusion, cold shuts or any other sharp crevice type indication shall not be acceptable. For acute angle fillets of 65 degrees or less, an unfused root not greater than 0.125 inch wide is acceptable. See Figure 6A.

4.5.4 Internal Discontinuities - "Internal discontinuities shall meet the requirements of NAS 1514 Class I, II and III".

4.6 Internal Quality Inspection - Nondestructive inspection shall be performed to assure compliance with the internal quality requirements of 4.5. Radiographic technique is the preferred inspection method; however, other techniques may be used in lieu of radiography if approved by the procuring agency.

4.6.1 Inspection Personnel - Personnel engaged in penetrant, radiographic, or alternate NDE techniques shall be qualified per MIL-STD-410.

4.6.1.1 Radiographic Inspection - Radiographic inspection shall be in accordance with MIL-STD-453.

4.6.1.2 A three to seven power optical magnifier shall be used as an aid in examination of radiographs to afford closer examination of suspect areas and to determine indication dimensions.

4.6.1.3 When reliability of inspection and critical flaw detection so dictate, redundant and/or complementing inspection techniques and procedures shall be employed.

4.6.2 Penetrant Inspection - Penetrant inspection shall be in compliance with MSFC-STD-366.

4.7 Records - A continuous record of weldment production quality shall be maintained. These records shall include the location of repairs, type of defects repaired, procedures used, and inches of repair per total inches of weld. These records shall be summarily accounted on a quarterly basis, with such accounting made available to the procuring agency upon request.

5. NOTES

5.1 Intended Use - Weld guideline and acceptance criteria for aerospace flight equipment and ground support equipment.

5.2 Ordering Data - Procurement documents should specify the title, number and date of this specification.

5.3 Definitions - Definitions pertaining to welding shall conform to the standard definitions of AWS A3.0 and the following paragraphs;

5.3.1 Material Thickness - The minimum material thickness of the thinnest joint member per drawing tolerance is designated "T".

5.3.2 Weld Intersection - As used herein, the term weld intersection refers to the meeting of two (or more) welds at a point where the second weld may or may not completely cross the first weld.

5.3.3 Welding Schedule - A detailed written procedure set forth as a permanent record which specifies the complete details regarding preweld preparation, welding parameters, and all pre and post-weld operations affecting the weld quality and/or properties of the joint.

5.4 Symbols

5.4.1 Welding/NDT Symbols - The standard welding and nondestructive testing symbols that are accepted for designation on drawings are listed in AWS A2.4.

5.5 Changes

5.5.1 Requests for deviation from, or waiver of, applicable paragraphs of specification should be directed to the procuning agency and to the Materials and Processes Laboratory, Marshall Space Flight Center, Alabama 35812, together with the supportive information.

MANUFACTURER'S RECORD OF WELDER OR WELDING OPERATOR QUALIFICATION TESTS

WELDER NAME _____ CHECK NO. _____ STAMP NO. _____
WELDING PROCESS _____ TYPE _____
IN ACCORDANCE WITH WELDING PROCEDURE SPECIFICATION (WPS) _____
BACKING _____
MATERIAL SPEC. _____
THICKNESS _____
FILLER METAL SPEC NO. _____ CLASS NO. _____ DIA. _____
OTHER _____
POSITION _____
GAS TYPE _____ % COMPOSITION _____
ELECTRICAL CHARACTERISTICS: CURRENT _____ POLARITY _____
WELD PROGRESSION _____
OTHER _____

GUIDED BEND TEST RESULTS

TYPE AND FIG. NO.	RESULT

RADIOGRAPHIC TEST RESULTS

FOR ALTERNATIVE QUALIFICATION OF GROOVE WELDS BY RADIOGRAPHY

RADIOGRAPHIC RESULTS _____

FILLET WELD TEST RESULTS

FRACTURE TEST (DESCRIBE THE LOCATION, NATURE, AND SIZE OF ANY CRACK OR TEARING OF THE SPECIMEN)

_____

LENGTH AND PERCENT OF DEFECTS _____ INCHES _____ % _____
MACRO TEST -- FUSION _____
APPEARANCE -- FILLET SIZE (LEG) _____IN. X_____ IN. CONVEXITY_____ IN. OR CONCAVITY_____ IN.

TEST CONDUCTED BY _____ LABORATORY - TEST NO. _____
WE CERTIFY THAT THE STATEMENTS IN THIS RECORD ARE CORRECT AND THAT THE TEST WELDS WERE PREPARED, WELDED, AND TESTED IN ACCORDANCE WITH THE REQUIREMENTS OF SECTION IX OF THE ASME CODE.

ORGANIZATION _____
DATE _____ BY _____

(DETAIL OF RECORD OF TESTS ARE ILLUSTRATIVE ONLY AND MAY BE MODIFIED TO CONFORM TO THE TYPE AND NUMBER OF TESTS REQUIRED BY THE CODE.)
NOTE: ANY ESSENTIAL VARIABLES IN ADDITION TO THOSE ABOVE SHALL BE RECORDED.

RECORD SHEET 1

WELDING PROCEDURE SPECIFICATION (WPS)

COMPANY NAME _____

WELDING PROCEDURE SPECIFICATION NO. _____ REV. _____ DATE _____

WELDING PROCESS(ES) _____ TYPE(S) _____

JOINTS

GROOVE DESIGN _____

BACKING: YES _____ NO _____

BACKING MATERIAL (TYPE) _____

OTHER _____

BASE METALS

PART NO. _____ TO PART NO. _____

THICKNESS RANGE, IN. _____

PIPE DIA. RANGE, IN. _____

OTHER _____

FILLER METALS

SPEC NO. _____

AWS NO. (CLASS) _____

SIZE OF ELECTRODE _____

SIZE OF FILLER _____

ELECTRODE FLUX (CLASS) _____

CONSUMABLE INSERT _____

OTHER _____

POSITION

POSITION OF GROOVE _____

WELDING PROGRESSION _____

OTHER _____

PREHEAT

PREHEAT TEMP. _____

INTERPASS TEMP. _____

PREHEAT MAINTENANCE _____

OTHER _____

POSTWELD HEAT TREATMENT

TEMPERATURE _____

TIME RANGE _____

OTHER _____

GAS

SHIELDING GAS(ES) _____

PERCENT COMPOSITION (MIXTURES) _____

FLOW RATE _____

GAS BACKING _____

TRAILING SHIELDING GAS COMPOSITION _____

OTHER _____

ELECTRICAL CHARACTERISTICS

CURRENT AC OR DC _____ POLARITY _____

AMPS(RANGE) _____ VOLTS(RANGE) _____

OTHER _____

TECHNIQUE

STRING OR WEAVE BEAD _____

ORIFICE OR GAS CUP SIZE _____

INITIAL AND INTERPASS CLEANING (BRUSHING, GRINDING, ETC.) _____

METHOD OF BACK GOUGING _____

OSCILLATION _____

CONTACT TUBE TO WORK DISTANCE _____

MULTIPLE OR SINGLE PASS (PER SIDE) _____

MULTIPLE OR SINGLE ELECTRODES _____

TRAVEL SPEED (RANGE) _____

OTHER _____

RECORD SHEET 2

PROCEDURE QUALIFICATION RECORD

COMPANY NAME _____

PROCEDURE QUALIFICATION RECORD NO. _____ DATE _____

WPS NO. _____

WELDING PROCESS(ES) _____

TYPES (MANUAL, AUTOMATIC, SEMI AUTO) _____

JOINTS

GROOVE DESIGN USED

BASE METALS

MATERIAL SPEC. _____

TYPE OR GRADE _____

THICKNESS _____

DIAMETER _____

OTHER _____

FILLER METALS

WELD METAL ANALYSIS _____

SIZE OF ELECTRODE _____

FILLER METAL _____

SPECIFICATION _____

AWS CLASSIFICATION _____

OTHER _____

POSITION

POSITION OF GROOVE _____

WELD PROGRESSION (UPHILL, DOWNHILL) _____

OTHER _____

PREHEAT

PREHEAT TEMP. _____

INTERPASS TEMP. _____

OTHER _____

POSTWELD HEAT TREATMENT

TEMPERATURE _____

TIME _____

OTHER _____

GAS

TYPE OF GAS OR GASES _____

COMPOSITION OF GAS MIXTURE _____

OTHER _____

ELECTRICAL CHARACTERISTICS

CURRENT _____

POLARITY _____

AMPS _____ VOLTS _____

OTHER _____

TECHNIQUE

TRAVEL SPEED _____

STRING OR WEAVE BEAD _____

OSCILLATION _____

MULTIPASS OR SINGLE PASS (PER SIDE) _____

SINGLE OR MULTIPLE ELECTRODES _____

OTHER _____

RECORD SHEET 3

TENSILE TEST

SPECIMEN NO.	WIDTH	THICKNESS	AREA	ULTIMATE TOTAL LOAD LB.	ULTIMATE UNIT STRESS PSI	CHARACTER OF FAILURE AND LOCATION

GUIDED BEND TESTS

TYPE AND FIGURE NO.	RESULT

TOUGHNESS TESTS

SPECIMEN NO.	NOTCH LOCATION	NOTCH TYPE	TEST TEMP.	IMPACT VALUES	DROP WEIGHT	
					BREAK	NO BREAK

FILLET WELD TEST

RESULT - SATISFACTORY: YES _____ NO _____ PENETRATION INTO PARENT METAL: YES _____ NO _____

MACRO-RESULTS _____

OTHER TESTS

TYPE OF TEST _____

DEPOSIT ANALYSIS _____

OTHER _____

WELDER'S NAME _____ CHECK NO. _____ STAMP NO. _____

TESTS CONDUCTED BY _____ LABORATORY TEST NO. _____

WE CERTIFY THAT THE STATEMENTS IN THIS RECORD ARE CORRECT AND THAT THE TEST WELDS WERE PREPARED, WELDED, AND TESTED IN ACCORDANCE WITH THE REQUIREMENTS OF MSFC-SPEC-766.

MANUFACTURER _____

DATE _____ BY _____

RECORD SHEET 3A

TABLE I

WELD PROCEDURE DATA

EACH CERTIFIED WELD PROCEDURE SHALL CONTAIN THE FOLLOWING DATA:

A. ENGINEERING DRAWING NUMBER _____.

B. INSPECTION CLASS _____.

C. PARENT MATERIAL _____: CONDITION _____.

D. FILLER MATERIAL _____: DIA: _____.

E. TOOL NUMBER _____: BACKUP CONFIGURATION____

_____:

F. WELD CHAMBER _____: SHIELDING GAS _____.

G. PRE-WELD CLEANING _____.

H. TUNGSTEN ELECTRODE TYPE _____: AND DIA._____.

I. POWER: CURRENT _____: VOLTS _____.

J. X-RAY REPORT _____.

TABLE II

WELD FILLER ALLOYS FOR TITANIUM AND TITANIUM ALLOY COMBINATIONS

PARENT METAL ALLOY COMBINATION	C.P.* TITANIUM	5 Al 2.5 Sn	5 Al 2.5 Sn ELI**	6 Al 4V	6 Al 4V ELI**	3 Al 2.5V		
CP* TITANIUM	1							
5 Al – 2.5 Sn	1	2,3						
5 Al 2.5 Sn ELI**	1	2,3	3					
6 Al – 4V	4,5	4,5	3,4,5	4,5	4,5			
6 Al – 4V ELI**		5	5	4.5	5			
3 Al 2.5V				4,5,6	4,5,6	6		

WELD FILLER ALLOY

1. C. P. * TITANIUM
2. Ti 5 Al – 2.5 Sn
3. Ti 5 Al – 2.5 Sn ELI**
4. Ti 6 Al – 4V
5. Ti 6 Al – 4V ELI**
6. Ti 3 Al – 2.5V

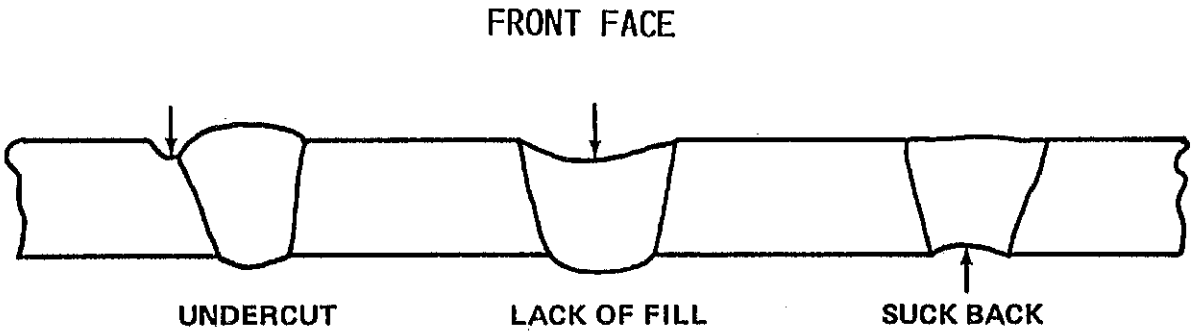
*COMMERCIALLY PURE
**EXTRA LOW INTERSTITTAL

TABLE III

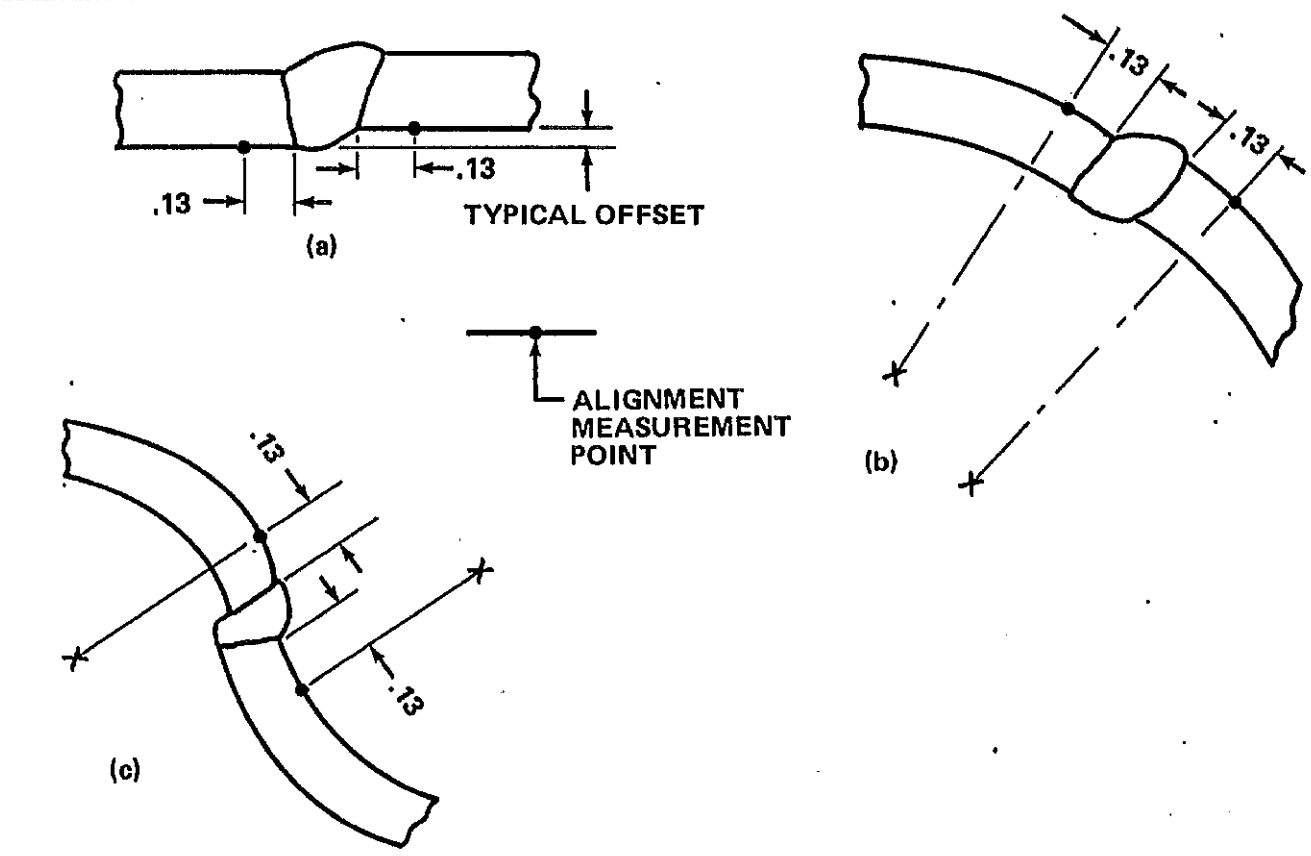
MINIMUM INSPECTION REQUIREMENTS

METHOD OF INSPECTION	WELD CLASS		
	I	II	III
VISUAL (See para. 3.11.2)	X	X	X
DIMENSIONAL	X	X	X
PENETRANT	X	X	0
RADIOGRAPH	X	see note	X
ADDITIONAL INSPECTION WHEN REQUIRED BY DRAWING	X	X	X

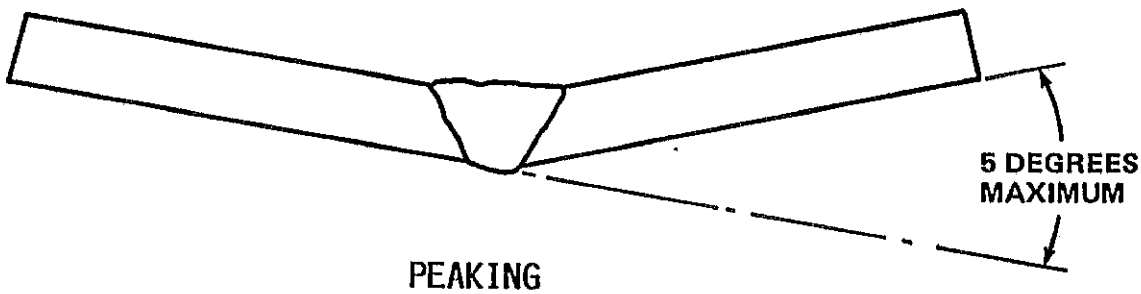
NOTE: CLASS II WELDS SHALL BE SUBJECTED TO RADIOGRAPHY IF REQUIRED BY ENGINEERING DESIGN AND SPECIFIED BY DRAWING OR SPECIAL INSTRUCTION.



TYPICAL WELD DEFECTS
FIGURE 1

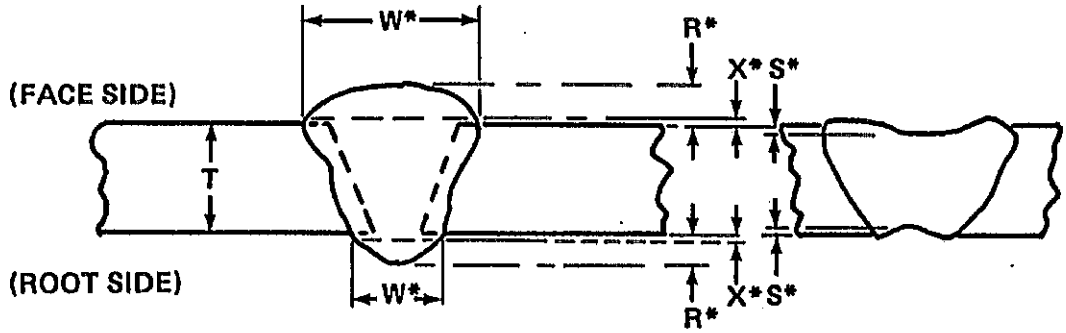


JOINT ALIGNMENT MEASUREMENT
FIGURE 2

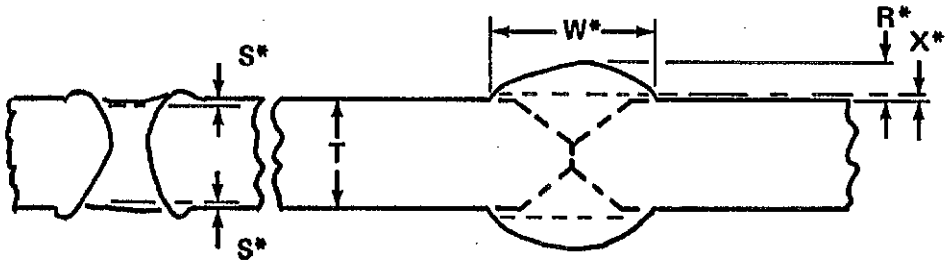


PEAKING

FIGURE 3



A - FULL PENETRATION JOINT-WELDED FROM ONE SIDE



NOTE:
S, W, R, X -- LIMITATIONS ARE THE SAME FOR BOTH SIDES OF WELD.

B - FULL PENETRATION JOINT-WELDED FROM BOTH SIDES

* NOTES: S (MAX) = MAXIMUM WELD BEAD CONCAVITY.
W (MAX) = MAXIMUM WIDTH OF WELD--BASED ON JOINT THICKNESS
R (MAX) = MAXIMUM REINFORCEMENT OF WELD--BASED ON JOINT THICKNESS
X (MIN) = MINIMUM REINFORCEMENT OF WELD--BASED ON JOINT THICKNESS

THE WELD MATERIAL CONTAINED WITHIN THE MINIMUM AND MAXIMUM REINFORCEMENT LIMITS (R--X) MAY BE REMOVED WITHOUT REWELDING.

FIGURE 4

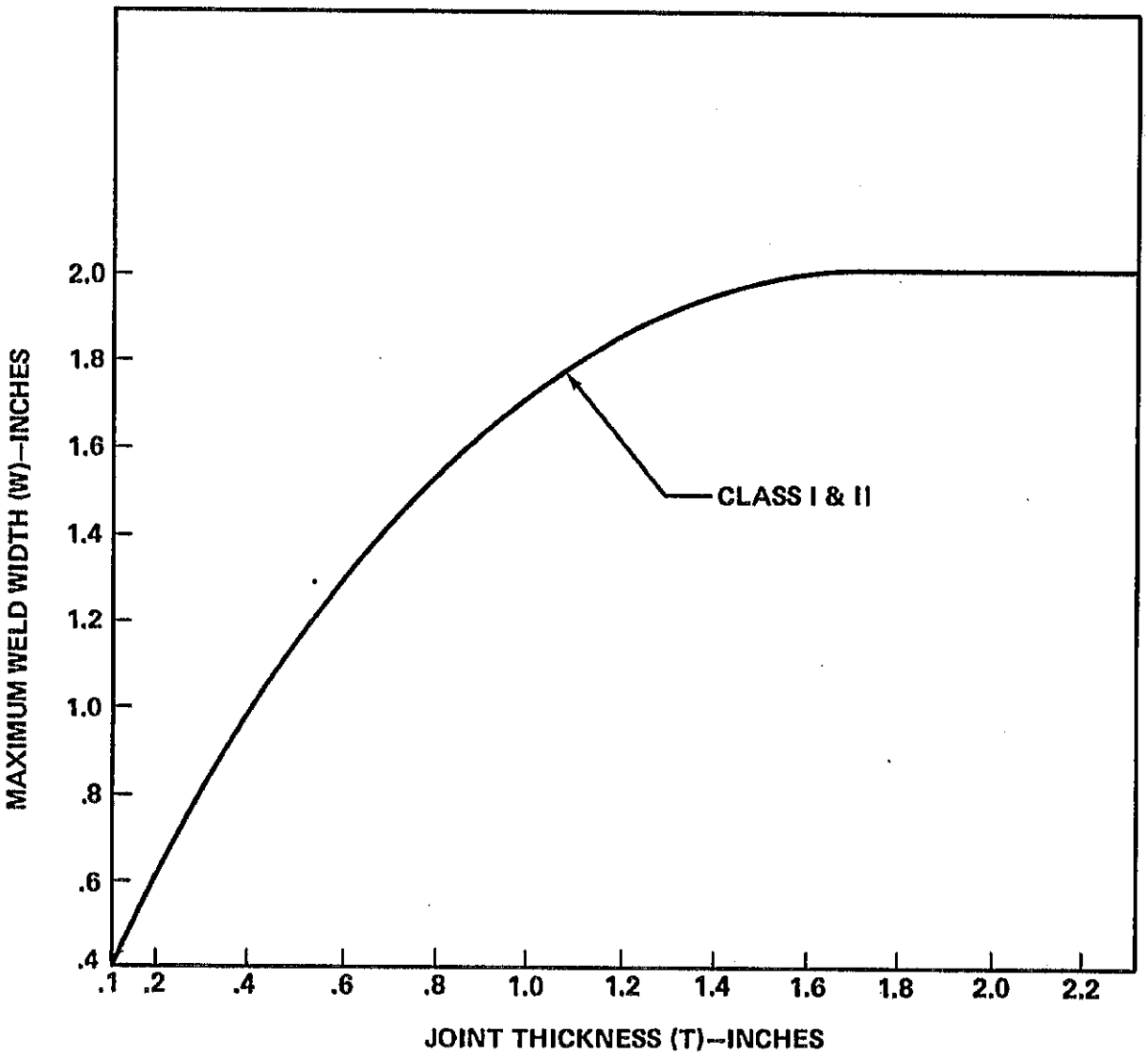


FIGURE 4A

MAXIMUM ALLOWABLE WELD WIDTH VS. THICKNESS-BUTT WELD

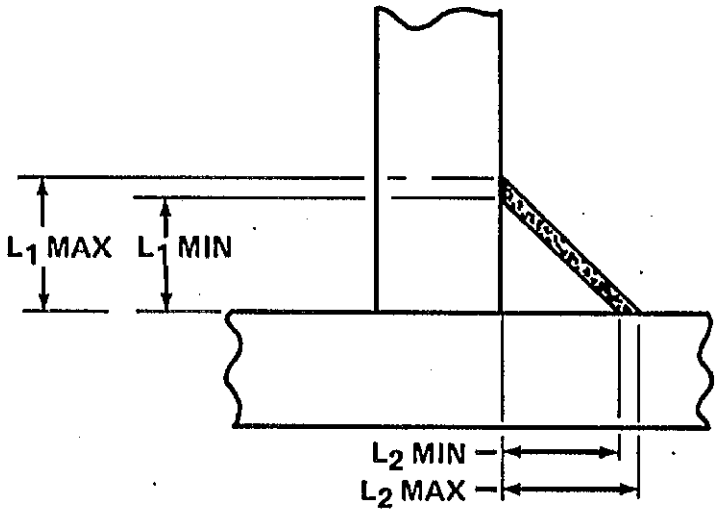
TABLE IV

S, X, R, AND W[1] LIMITS FOR BUTT WELDS

THICKNESS NOMINAL, IN.		CLASS I WELD	CLASS II WELD
0 THRU .01	S (MAX)	0	.05T
	X (MIN)	0	0
	R (MAX)	.5T + .02	.5T + .02
	W (MAX)	.09	.09
.01 TO .02	S	0	.05T
	X	0	0
	R	.5T + .02	.5T + .02
	W	.18	.18
.02 TO .03	S	0	.05T
	X	0	0
	R	.3T + .02	.3T + .02
	W	.18	.18
.03 TO .05	S	0	.05T
	X	0	0
	R	.3T + .02	.3T + .02
	W	5.0T	5.0T
.05 TO .10	S	0	.05T
	X	0	0
	R	.4T + .02	.4T + .02
	W	4.0T	4.0T
.10 AND OVER	S	0	.05T OR .03*
	X	.05T OR .03*	0
	R	.6T OR .09*	.6T + .12
	W	PER FIG. 4A	PER FIG. 4A

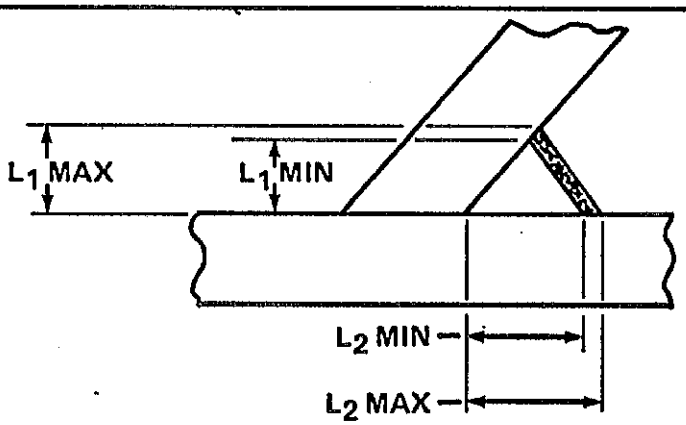
NOTE 1: SEE FIGURE 4 FOR DEFINITIONS

*WHICHEVER IS LESS



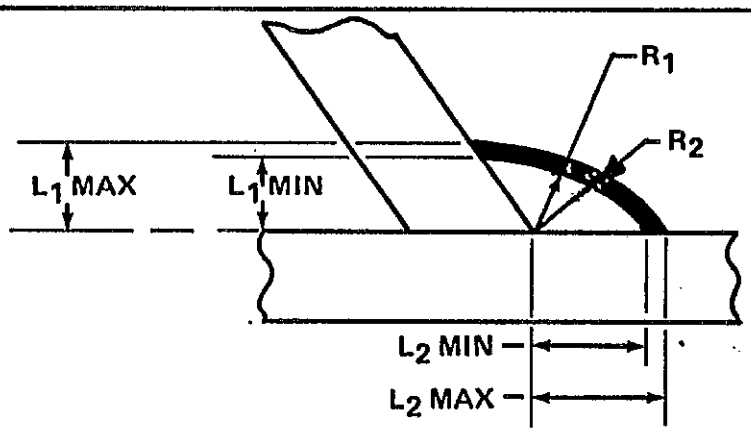
NOTE: THE WELD PROFILE SHALL BE CONTAINED WITHIN THE SHADED AREA

5A - RIGHT ANGLE FILLET WELD



NOTE: THE WELD PROFILE SHALL BE CONTAINED WITHIN THE SHADED AREA.

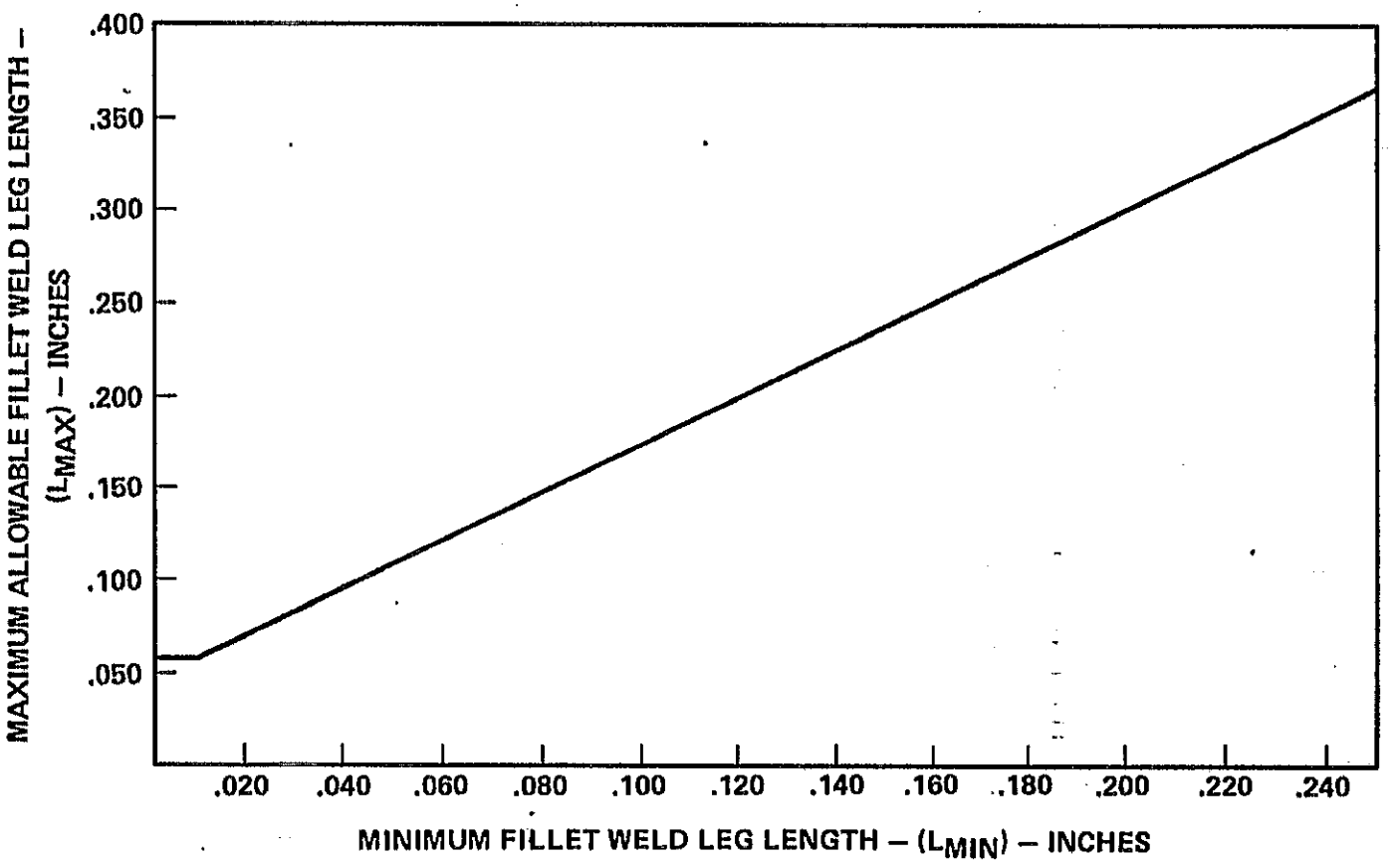
5B - ACUTE ANGLE FILLET WELD



NOTE: THE WELD PROFILE SHALL BE CONTAINED WITHIN THE SHADED AREA BOUNDED BY RADII R_1 AND R_2.

5C - OBTUSE ANGLE FILLET WELD

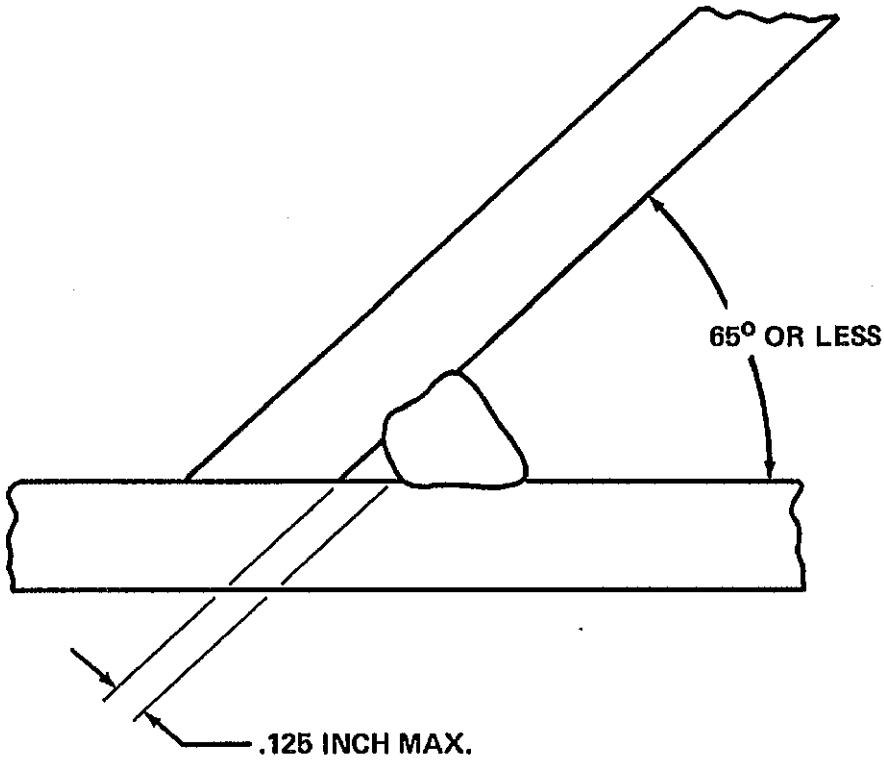
FIGURES 5A, 5B, 5C



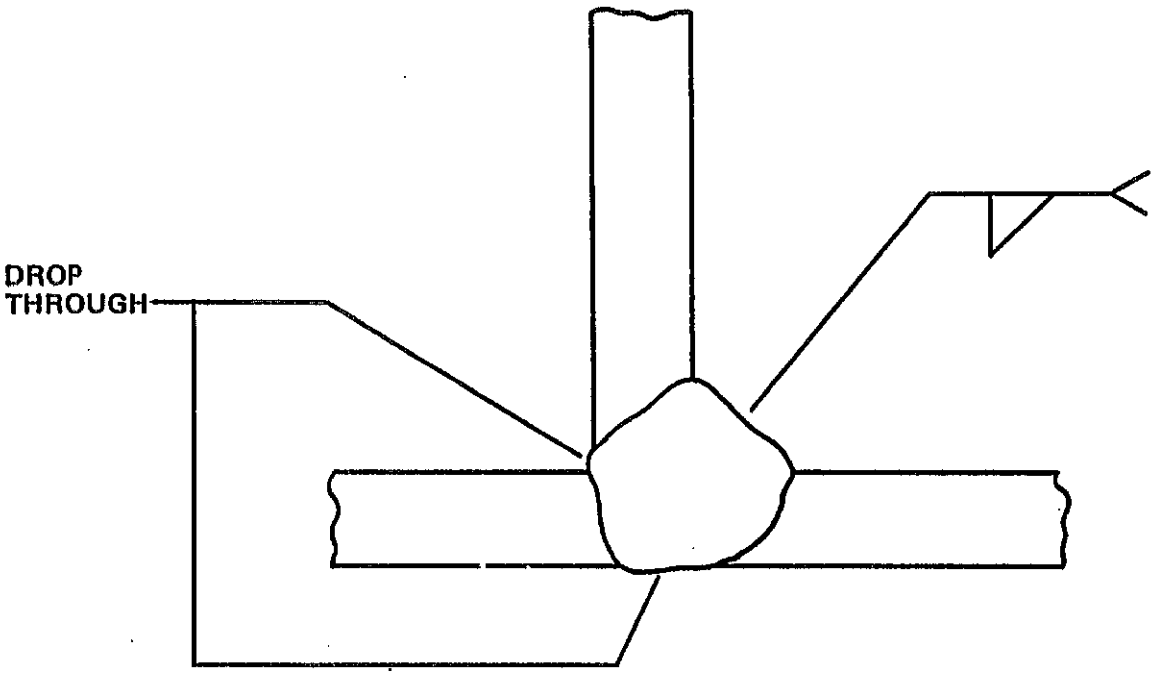
NOTE: THE MAXIMUM LEG LENGTH IN WELDS OF .251" OR GREATER – DESIGNATED SIZE (L) SHALL BE L +.12 INCH.

FIGURE 5D

MAXIMUM FILLET WELD SIZE



A - ACUTE ANGLE FILLET WELD-UNFUSED ROOT



B - FILLET WELD DROP THROUGH

FIGURES 6A, 6B

Specification: FUSION WELDING TITANIUM AND TITANIUM ALLOYS

Approved by: R. J. Schwinghamer

R. J. Schwinghamer
Director
Materials and Processes Laboratory

Custodian:

NASA - George C. Marshall Space Flight Center

Preparing Agency:

George C. Marshall Space Flight Center

PACKAGE NO. 10443R

DOCUMENTATION RELEASE LIST
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C H	DOCUMENT NUMBER	DRL DSH	DRL REV	TITLE	CCBD NO.	PCN	PC	EFFECTIVITY
*	MSFC-SPEC-766	202	-	FUSION WELDING TITANIUM ALLOYS	000-00-0000	0000000	S	NONE

CHG NO.	CHG REV	CHG NOTICE	RESPONSIBLE ENGINEER	RESPONSIBLE ORGANIZATION	ACTION DATE	DESCRIPTION
			W. A. WILSON	EH42	03/22/94	BASELINE RELEASE
*	1	SCN000	EUGENA GOGGANS	EO03	02/22/07	DOCUMENT RELEASED THRU PDS. NO LONGER TRACKED IN ICMS.

CHECKER

N/A
02/15/07

(FINAL)

PACKAGE NO: 10443R

PROGRAM/PROJECT: MULTI LAST UPDATED: 02/22/07

NOMENCLATURE: MSFC-STD- GOING TO NONE EFFECTIVITY

ECR NO:	PCN:	CCBD NO:	DATE PREPARED:
E003-0000	0000000	000-00-0000	02/22/07
		SB3-00-0000	

DWG SIZE	DRAWING NUMBER	DWG REV	EPL/DRL/DDS NUMBER	DWG REV	EPL DSH	EPL REV	EO DASH NUMBER	EO REV	PART NUMBER
			MSFC-HDBK-1453		202	-			
			MSFC-HDBK-1674		202	-			
			MSFC-HDBK-2221		203	-			
			MSFC-HDBK-505		202	-			
			MSFC-HDBK-670		202	-			
			MSFC-MNL-1951		209	-			
			MSFC-PROC-1301		202	-			
			MSFC-PROC-1721		202	-			
			MSFC-PROC-1831		202	-			
			MSFC-PROC-1832		202	-			
			MSFC-PROC-404		202	-			
			MSFC-PROC-547		202	-			
			MSFC-QPL-1918		204	-			
			MSFC-RQMT-1282		202	-			
			MSFC-SPEC-1198		202	-			
			MSFC-SPEC-1238		202	-			
			MSFC-SPEC-1443		202	-			
			MSFC-SPEC-164		202	-			
			MSFC-SPEC-1870		202	-			
			MSFC-SPEC-1918		203	-			
			MSFC-SPEC-1919		206	-			
			MSFC-SPEC-2083		202	-			
			MSFC-SPEC-2223		202	-			
			MSFC-SPEC-2489		206	-			
			MSFC-SPEC-2490		205	-			
			MSFC-SPEC-2491		203	-			
			MSFC-SPEC-2492		203	-			
			MSFC-SPEC-2497		211	-			
			MSFC-SPEC-250		202	-			
			MSFC-SPEC-445		202	-			
			MSFC-SPEC-504		202	-			
			MSFC-SPEC-521		202	-			
			MSFC-SPEC-548		202	-			
			MSFC-SPEC-560		202	-			
			MSFC-SPEC-626		202	-			
			MSFC-SPEC-684		202	-			
			MSFC-SPEC-708		202	-			
			MSFC-SPEC-766		202	-			
			MSFC-STD-1249		202	-			
			MSFC-STD-1800		202	-			
			MSFC-STD-246		202	-			
			MSFC-STD-2594		203	-			

PACKAGE NO: 10443R

DWG SIZE	DRAWING NUMBER	DWG REV	EPL/DRL/DDS NUMBER	DWG REV	EPL DSH	EPL REV	EO DASH NUMBER	EO REV	PART NUMBER
			MSFC-STD-2903		202	-			
			MSFC-STD-2904		202	-			
			MSFC-STD-2905		202	-			
			MSFC-STD-2906		202	-			
			MSFC-STD-2907		202	-			
			MSFC-STD-366		202	-			
			MSFC-STD-383		202	-			
			MSFC-STD-486		202	-			
			MSFC-STD-506		203	-			
			MSFC-STD-531		202	-			
			MSFC-STD-557		202	-			
			MSFC-STD-561		203	-			
			MSFC-STD-781		202	-			

SUBMITTED BY ENGINEERING AREA:	BASIC CHANGE	PARTIAL	COMPLETE	CLOSES ACTION
EO03	X		X	EO03

PREPARED BY:
EUGENA GOGGANS
12/19/06

SUBMITTED BY:

CONCURRENCE:

TRANSMITTAL DATES
TO RELEASE DESK 02/22/07 10:00
TO MSFC DOC REP 02/22/07 00:00

REMARKS:

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I. GENERAL INFORMATION

1. APPROVED PROJECT:	2. DOCUMENT/ DRAWING NUMBER:	3. CONTROL NUMBER:	4. RELEASE DATE:	5. SUBMITTAL DATE:
	MSFC-SPEC-766		02/04/1983	10/27/2002

6. DOCUMENT/DRAWING TITLE:	7. REPORT TYPE:
Fusion Welding, Titanium and Titanium Alloys	Specification

8. CONTRACT NUMBER / PERFORMING ACTIVITY:	9. DRD NUMBER:	10. DPD / DRL / IDRD NUMBER:

11. DISPOSITION AUTHORITY (Check One):	12. SUBMITTAL AUTHORITY:	13. RELEASING AUTHORITY:
☒ Official Record - NRRS 8/12/A ☒ Reference Copy - NRRS 8/5/A/3 (destroy when no longer needed)		MB Cook

14. SPECIAL INSTRUCTIONS:

15. CONTRACTOR/SUBMITTING ORGANIZATION, ADDRESS AND PHONE NUMBER:	16. ORIGINATING NASA CENTER: Marshall Space Flight Center 17. OFFICE OF PRIMARY RESPONSIBILITY: ED33

18. PROGRAMMATIC CODE (5 DIGITS):	19. NUMBER OF PAGES:

II. ENGINEERING DRAWINGS

20. REVISION:	21. ENGINEERING ORDER:	22. PARTS LIST:	23. CCBD:

III. REPORTS, SPECIFICATIONS, ETC.

24. REVISION:	25. CHANGE:	26. VOLUME:	27. BOOK:	28. PART:	29. SECTION:

30. ISSUE:	31. ANNEX:	32. SCN:	33. DCN:	34. AMENDMENT:

35. APPENDIX:	36. ADDENDUM:	37. CCBD:	38. CODE ID:	39. IRN:

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40. ORG. CODE:	41. PHONE NUMBER:	42. NAME:	43. SIGNATURE/DATE:
ED33	4-2705	Carolyn Russell	Wayne R. Dumas Jr 10/15/03

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