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AEROSPACE INFORMATION REPORT

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CRACK INITIATION AND GROWTH CONSIDERATIONS FOR LANDING GEAR STEEL WITH EMPHASIS ON AERMET 100

1. SCOPE:

Steel alloys, such as AF1410 (AMS 6527, UNS K92571) and AerMet 100 (AMS 6532), have been developed which have improved Fracture Toughness characteristics compared to the current landing gear steel alloy, 300M (AMS 6419 and AMS 6257, MIL-S-8844, UNS K44220). The 300M steel is the most widely used material in current landing gear designs. It has been successfully used in thousands of applications. The use of the 300M material necessitates a safe life design criterion where components are retired after one-fourth to one-sixth the laboratory test life. This criterion was established in part due to the relatively low fracture toughness of low-alloy steel in the 260 to 300 ksi strength range.

The high fracture tough alloys give comparable strength levels with an increase in fracture toughness and better resistance to stress corrosion cracking. These alloys may make possible the consideration of new procedures for operation, maintenance, and inspection. For the present, these materials in the 220 to 280 ksi strength range, cannot be certified to damage tolerant design criteria. They may not yield critical cracks readily detectable using normal in-service inspection methods. Even though they may not qualify as damage tolerant in single load path applications, the improved mechanical properties alone may justify the consideration of these materials, especially in corrosive environments. In the future, they may allow on-condition maintenance, crack growth monitoring, and increased potential for rework.

This document identifies several available materials. It compares properties of selected low-alloy steels to the higher alloyed steels. It also compares failure modes, maintenance, and inspection techniques. Although cost should be a factor when considering the material selection for landing gear application, this document will only focus on the technical aspects.

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2. REFERENCES:

(1) "Comparative Data of High Strength Aerospace Alloys" (Carpenter Technology Corporation).

(2) "AerMet 100 - An Advanced Steel for the Aerospace Industry", James Dahl, Carpenter Technology Corporation, reprinted from Advanced Materials Technology International, 1991.

(3) "Aerospace Materials Handbook", Vol. 1, Code 1217, 1987.

(4) "Combined Strength and Toughness Characterize New Aircraft Alloy", Thomas J. McCaffrey, Carpenter Technology Corp., printed in Advanced Materials & Processes, Volume 142, Number 3, Sept 1992.

(5) "AerMet 100 Alloy for Landing Gear Applications - A Summary of Forging Studies", SAE Aerotech '92: Presentation by Michael L. Schmidt, Senior Metallurgist, Tool and Alloy R&D, Carpenter Technology Corp., SAE Paper 922041.

(6) Reports of Machinability Studies Conducted by Bendix Wheels and Brakes Division of Allied-Signal Aerospace, Westmoreland Mechanical Testing & Research Inc., Carpenter Technology Corp., and Waukesha Cutting Tools, Inc. in calendar year 1992.

(7) "Fatigue Crack Growth in AerMet 100 Steel", Report Nos. AD-A249068 and NADC-91111-60, dated 18 Oct 1991 by Eun U. Lee, Air Vehicle and Crew Systems Technology Directorate (Code 6063), Sponsor N0000154 Naval Air Development Center.

(8) MIL-HDBK-5F, Change Notice 2, 15 Dec 1992, Section 2.5.3.

(9) "875 °F (5 h) Aged AerMet 100: Data for AMS and MIL-HDBK-5 Specifications", CarTech Research and Development, Paul M. Novotny, Metallurgist, Tool & Alloy R&D.

(10) "Corrosion of Landing Gear Steels", E. U. Lee, J. Kozol, J. B. Boodey, J. Waldman, Naval Air Warfare Center, Aircraft Division Warminster, Warminster, PA 18974, USA.

3. MATERIALS:

The steel alloy 300M is a traditional quench and temper, low-alloy steel. This steel is usually used in the 280 to 300 ksi ultimate tensile strength range. The prime candidates for supplementing the low-alloy steels in current use, are AF1410 and AerMet 100. They are highly alloyed, martensitic precipitation/age hardening alloys (maraging steels).

4. MATERIAL PROPERTIES:

4.1 Mechanical Properties:

Comparisons of several mechanical properties for AF1410, AerMet 100, and 300M are shown in Figures 1 through 6 (1). For illustration, properties for H11 medium-alloy steel and Hy-Tuf steel are included. In general, AerMet 100 exceeds 300M for yield strength and fracture toughness at an equal or greater ultimate tensile strength. AF1410 falls slightly lower than 300M for yield and tensile strengths at a much greater fracture toughness. (2)

4.2 Fracture Toughness:

AF1410 and AerMet 100 alloys offer significant advantages over 300M in fracture toughness capabilities. Typical KIc fracture toughness values are 50 ksi√in at 290 ksi UTS for 300M. This value is compared to 105 ksi√in at 285 ksi UTS for AerMet 100 and 140 ksi√in at 240 ksi UTS for AF1410. Similar improvements are noted for the Charpy V-Notch impact fracture test. Typical values are 15 ft lbf for 300M steel, 30 ft lbf for AerMet 100 and 45 ft lbf for AF1410. (2)

4.3 Fatigue Properties and Crack Growth:

Based on fatigue test data, AerMet 100 ranks highest followed by AF1410 and the other low-alloy steels (1) (2).

Test Conditions:

The fatigue behavior of AerMet 100 steel was investigated under constant amplitude loading in inert and corrosive environments. The AerMet used in this study was initially forged at 1850 °F and annealed at 1250 °F for 16 hours. It was subjected to the following heat treatment:

1. Solution treatment at 1625 °F for 1 hour and air cooling
2. Deep freezing at -100 °F for 1 hour and air warming
3. Aging at 900 °F for 5 hours and air cooling

Material Properties:

Test sample mechanical properties in the longitudinal orientation compared to standard AMS 6532 properties were:

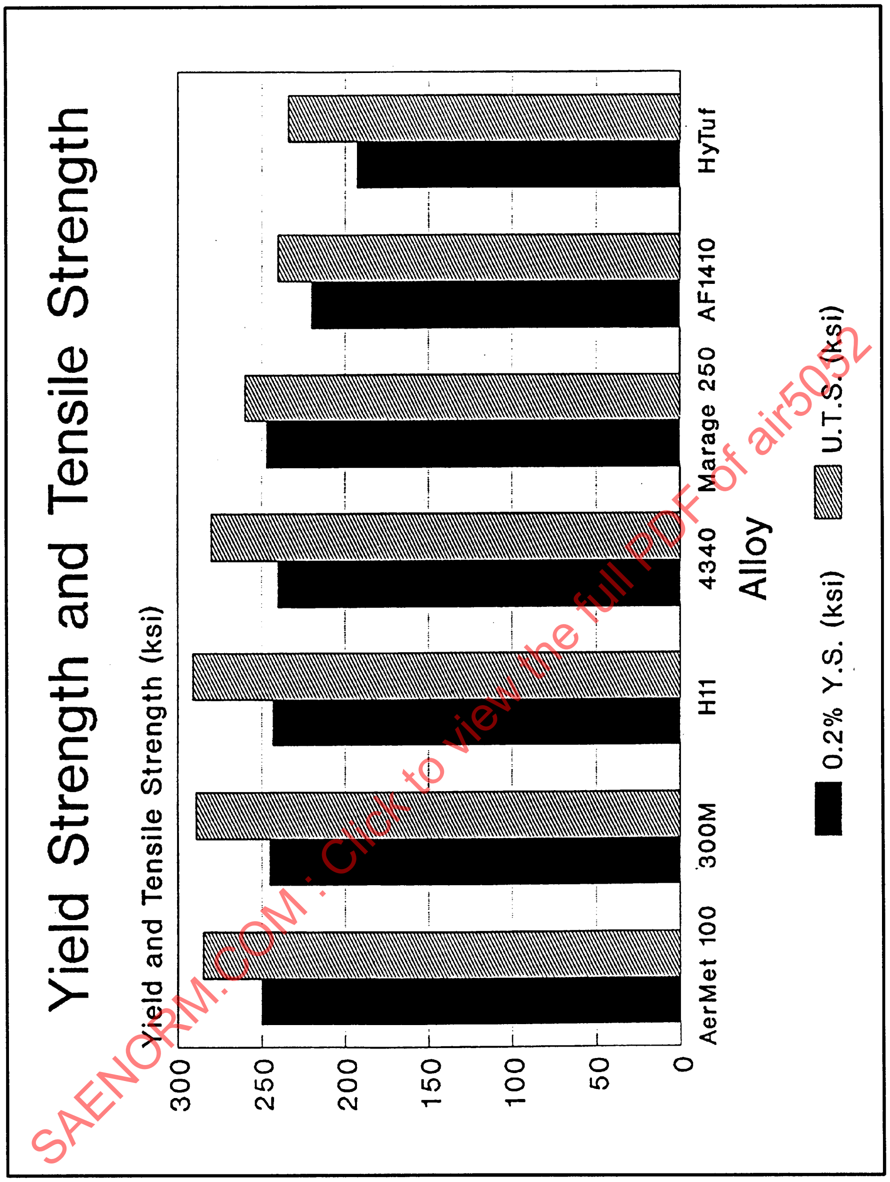

FIGURE 1 - Yield Strength and Tensile Strength

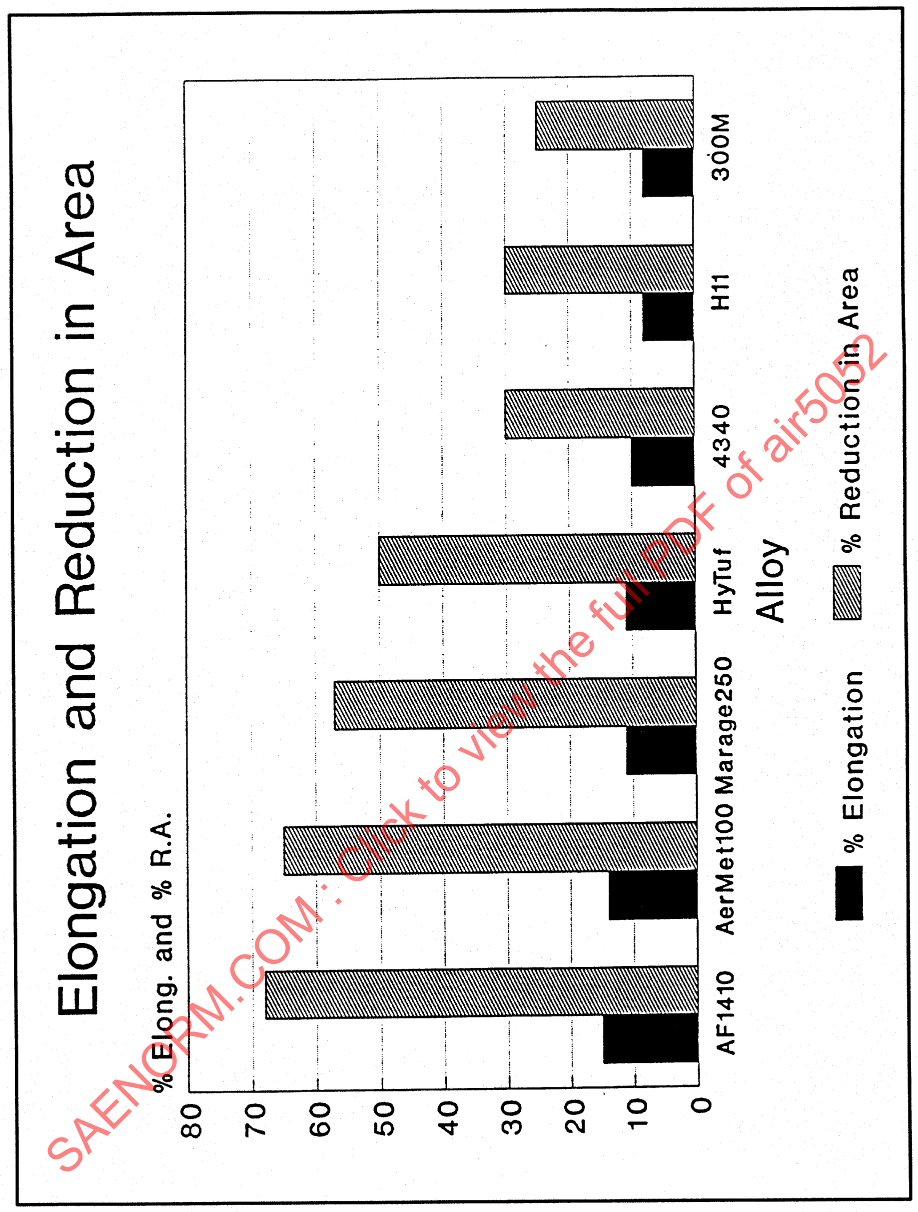

FIGURE 2 - Elongation and Reduction in Area

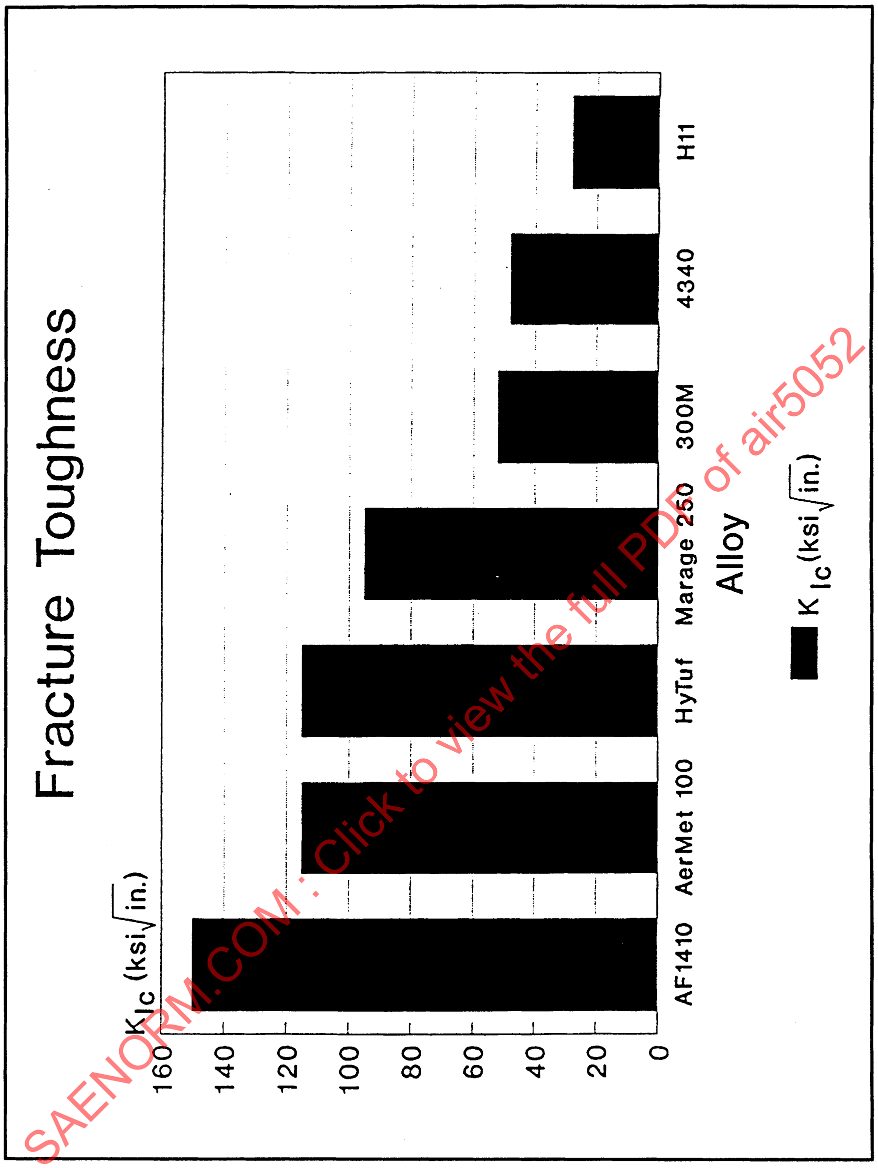

FIGURE 3 - Fracture Toughness

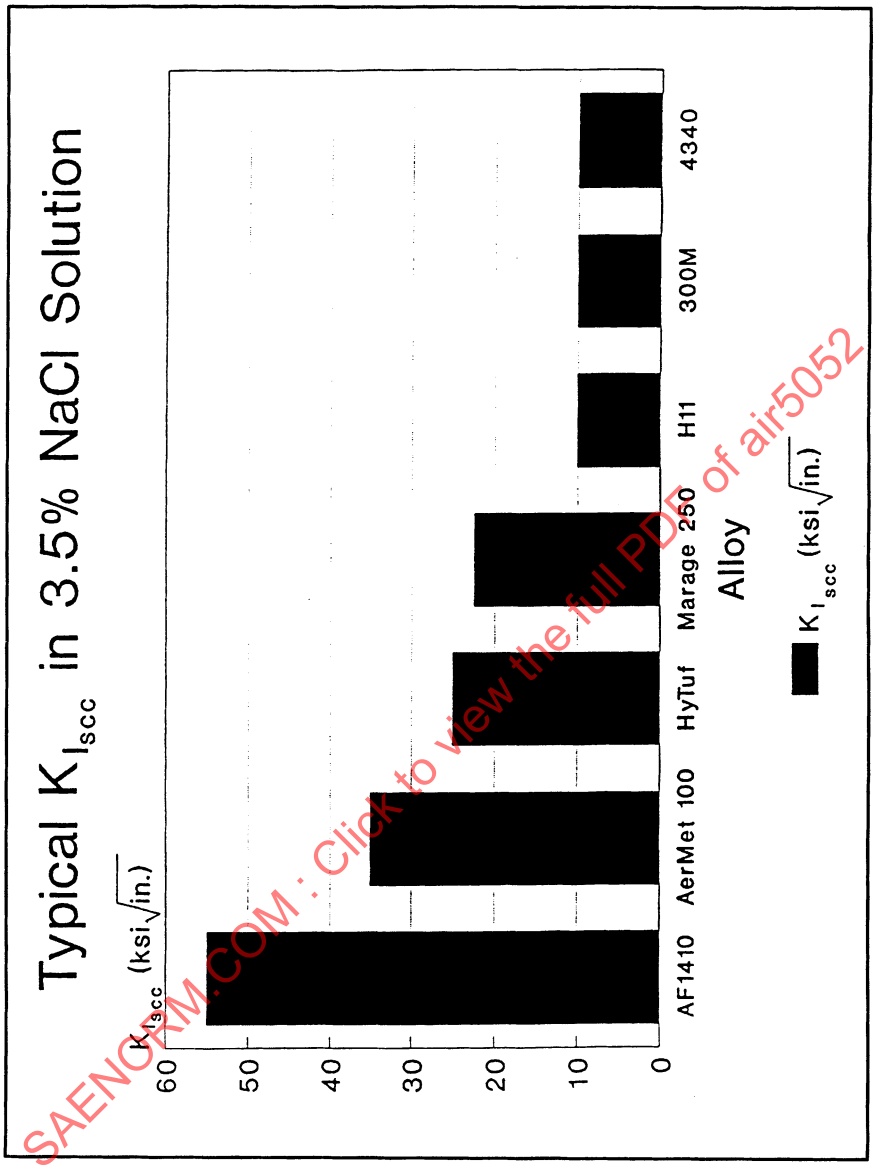

FIGURE 4 - Typical K_{Iscc} in 3.5% NaCl Solution

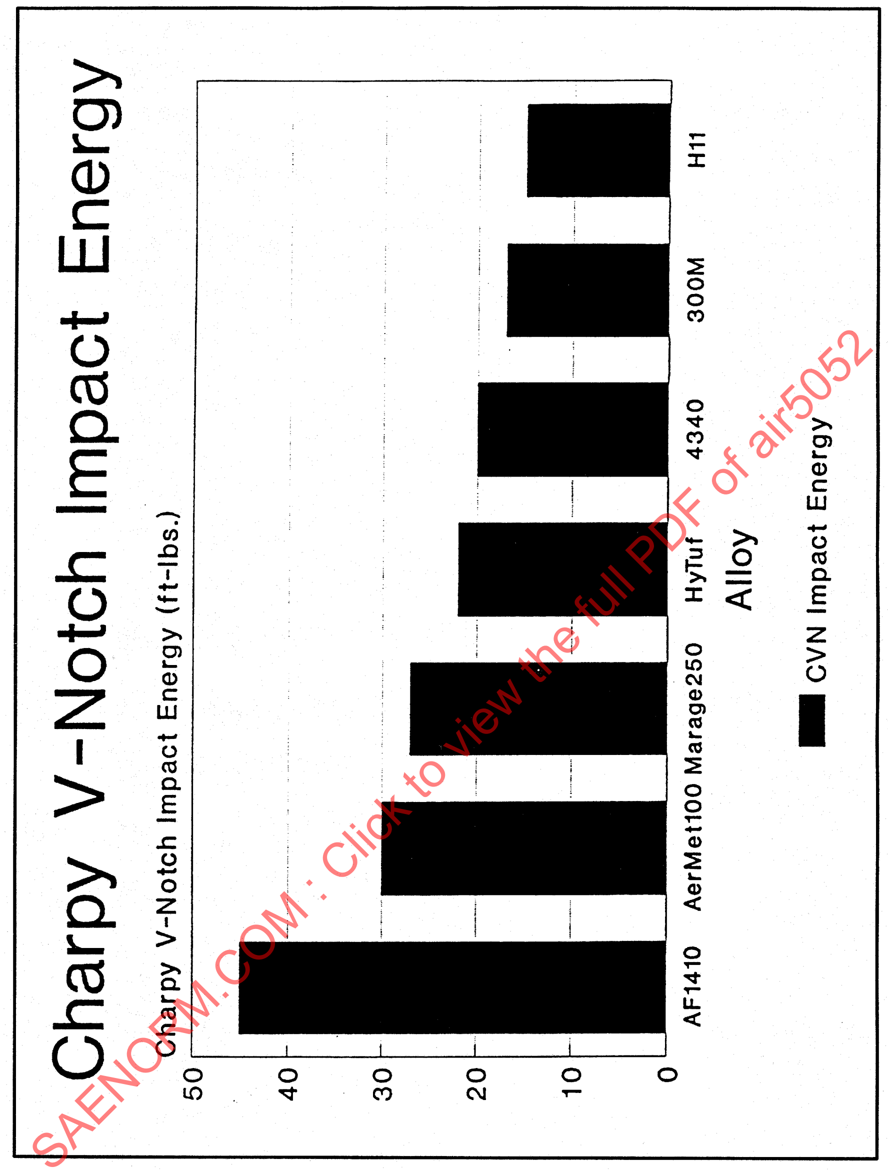

FIGURE 5 - Charpy V-Notch Impact Energy

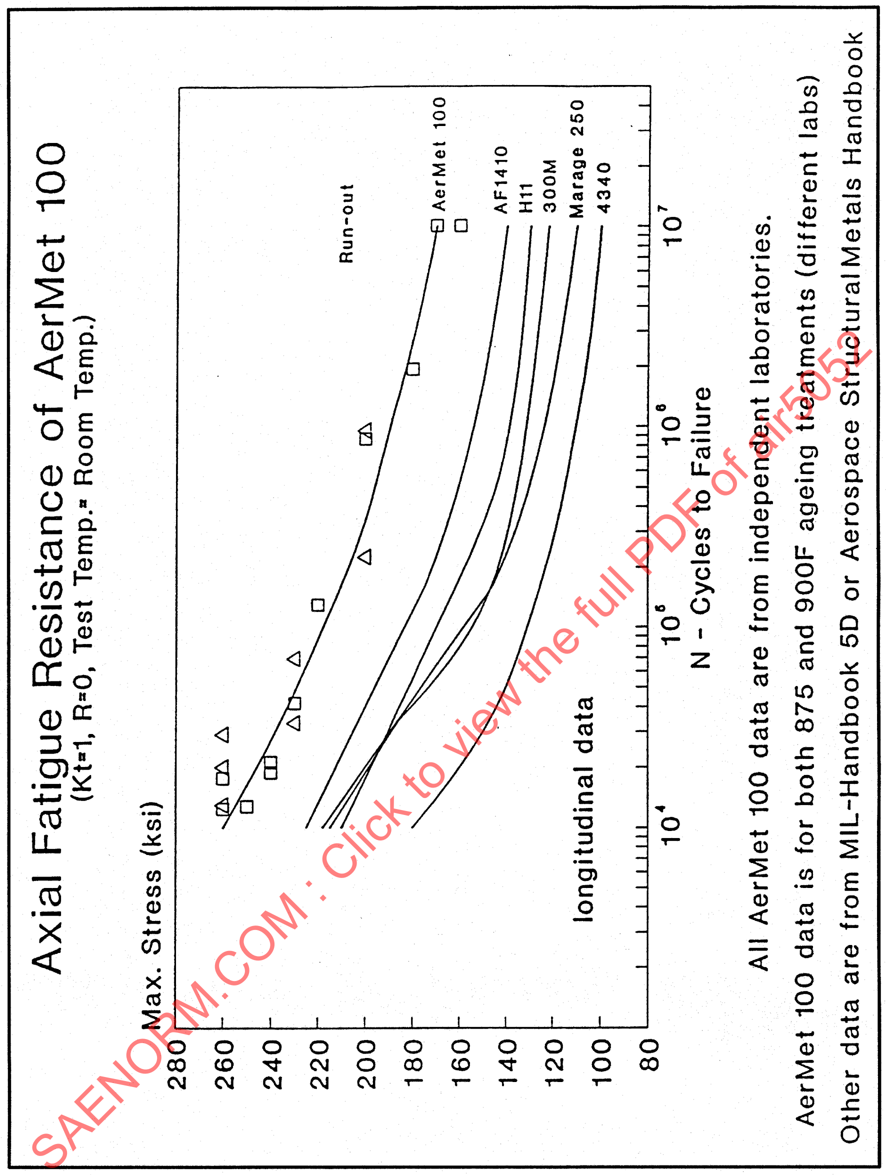

FIGURE 6 - Axial Fatigue Resistance of AerMet 100

TABLE 1

	Test Sample	AMS 6532 Per MIL-HDBK-5F
Yield Strength (ksi)	250	235
Tensile Strength (ksi)	285	280
Elongation (%)	14	10
Reduction of Area (%)	65	55
KIc (ksi√in)	115	
Modules (1000 ksi)	28.2	28.2
Density (lb/in^3)	.285	.285

4.3 (Continued):

Conclusions:

Based on a study of fatigue crack growth in AerMet 100 steel, tested in dry nitrogen gas and a 3.5% NaCl solution, the following conclusions can be drawn:

1. The fatigue crack growth resistance of the AerMet 100 Steel is superior to that of the 300M steel in inert and corrosive environments.

2. The significant features of fatigue crack growth in the AerMet 100 steel are:

   (a) Near threshold fatigue crack growth rates, below 10E-6 in/cycle, are faster in dry nitrogen gas than in a 3.5% NaCl solution due to corrosion product induced crack closure.

   (b) For each of the employed stress ratios, R = 0.1, 0.5 and 0.8, the delta K threshold value is less in dry nitrogen gas than in a 3.5% NaCl solution.

   (c) The larger the stress ratio, the greater is the near-threshold fatigue crack growth rate and the smaller is the delta K threshold value in both environments.

   (d) At high fatigue crack growth rates, above 10E-6 in/cycle, the effects of environment and stress ratio are substantially reduced.

   (e) The near-threshold fatigue crack growth behavior in a 3.5% NaCl solution is attributed to a mechanism involving corrosion-product-induced crack closure.

See Figures 7 through 14. (7)

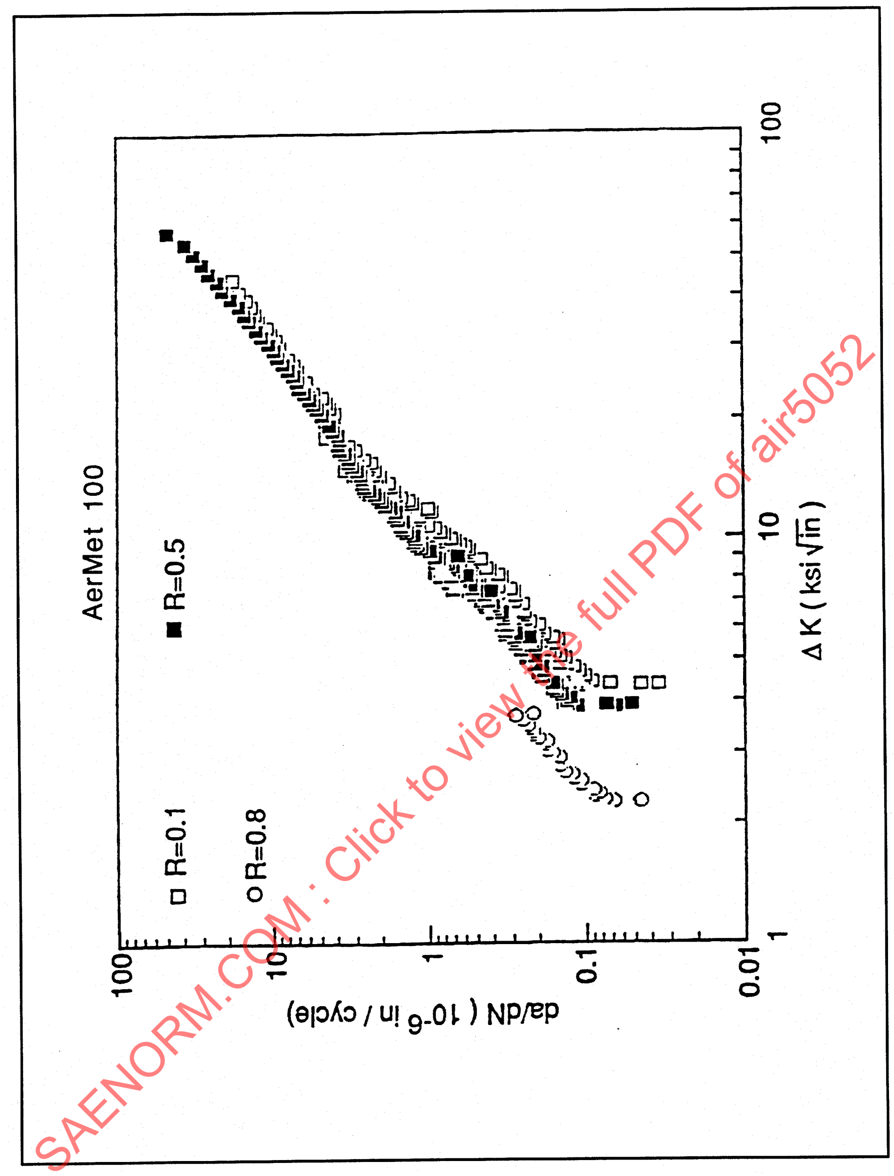

FIGURE 7 - Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for Stress Ratio R = 0.1, 0.5 and 0.8 in Dry Nitrogen Gas

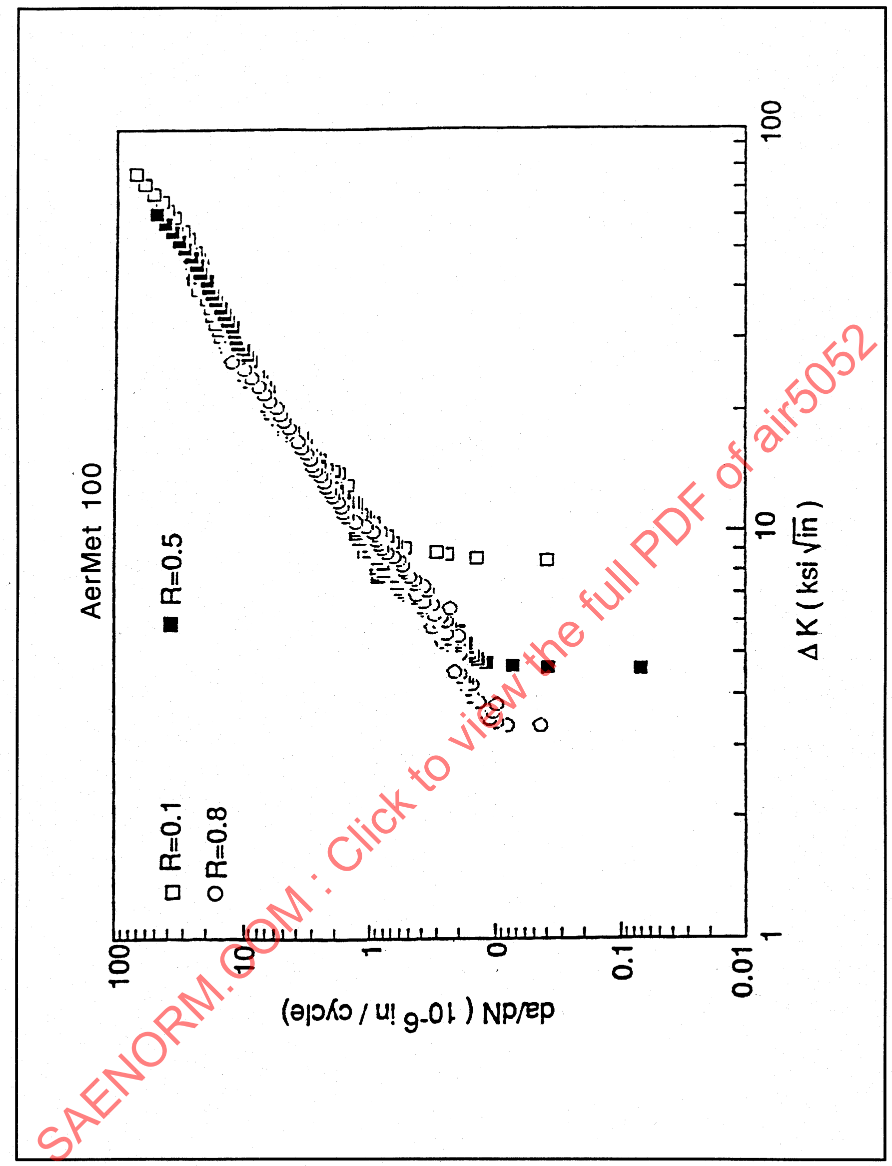

FIGURE 8 - Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for Stress Ratio R = 0.1, 0.5 and 0.8 in a 3.5% NaCl Solution

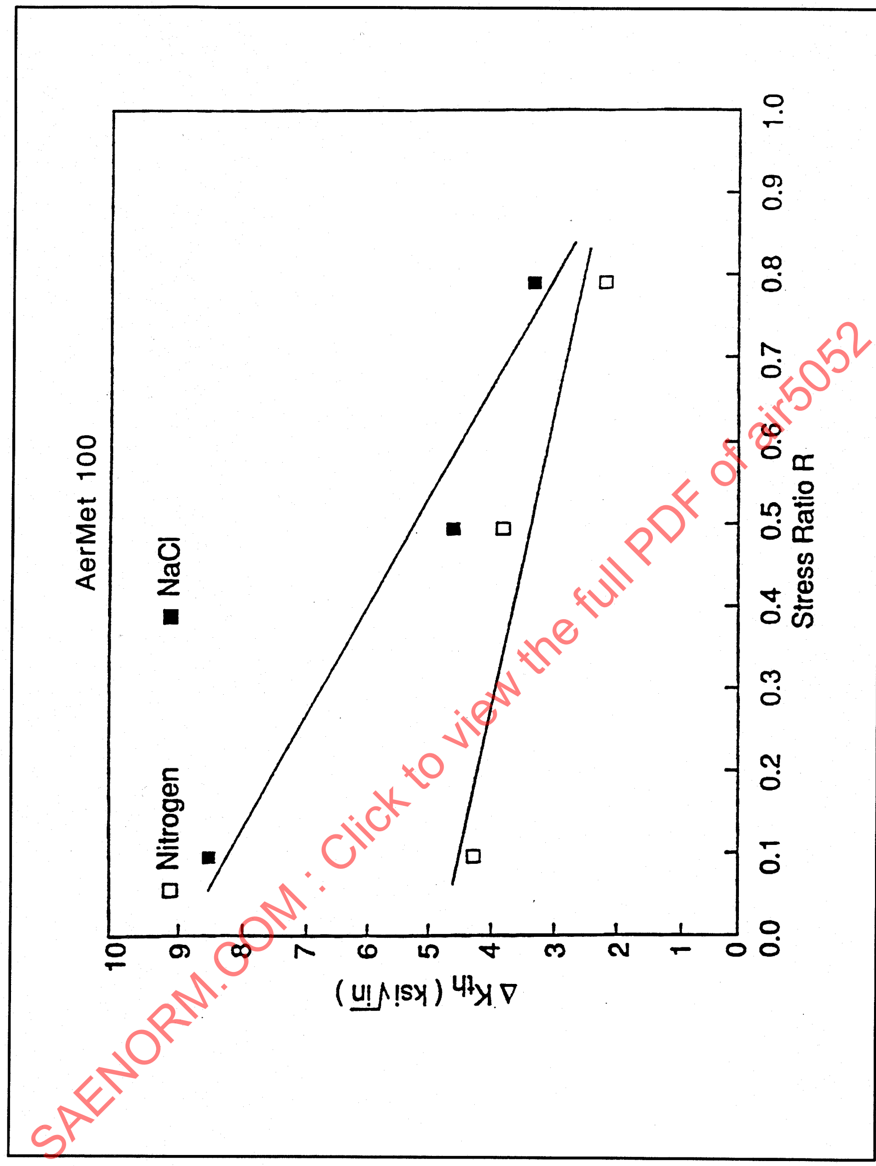

FIGURE 9 - Variation of Threshold Stress Intensity Range for Fatigue Crack Growth, ΔK_{th} with Stress Ratio, R, in Dry Nitrogen Gas and a 3.5% NaCl Solution

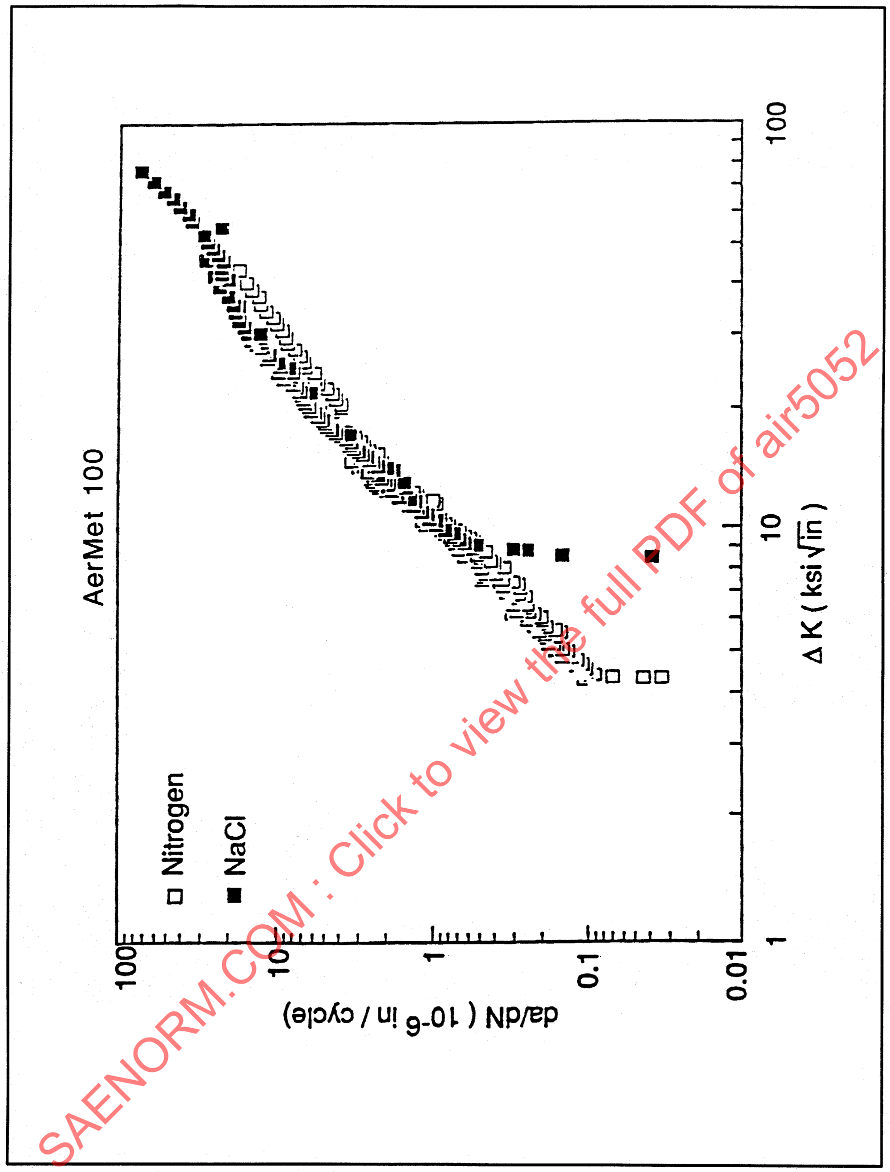

FIGURE 10 - Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for Stress Ratio R = 0.1 in Dry Nitrogen Gas and a 3.5% NaCl Solution

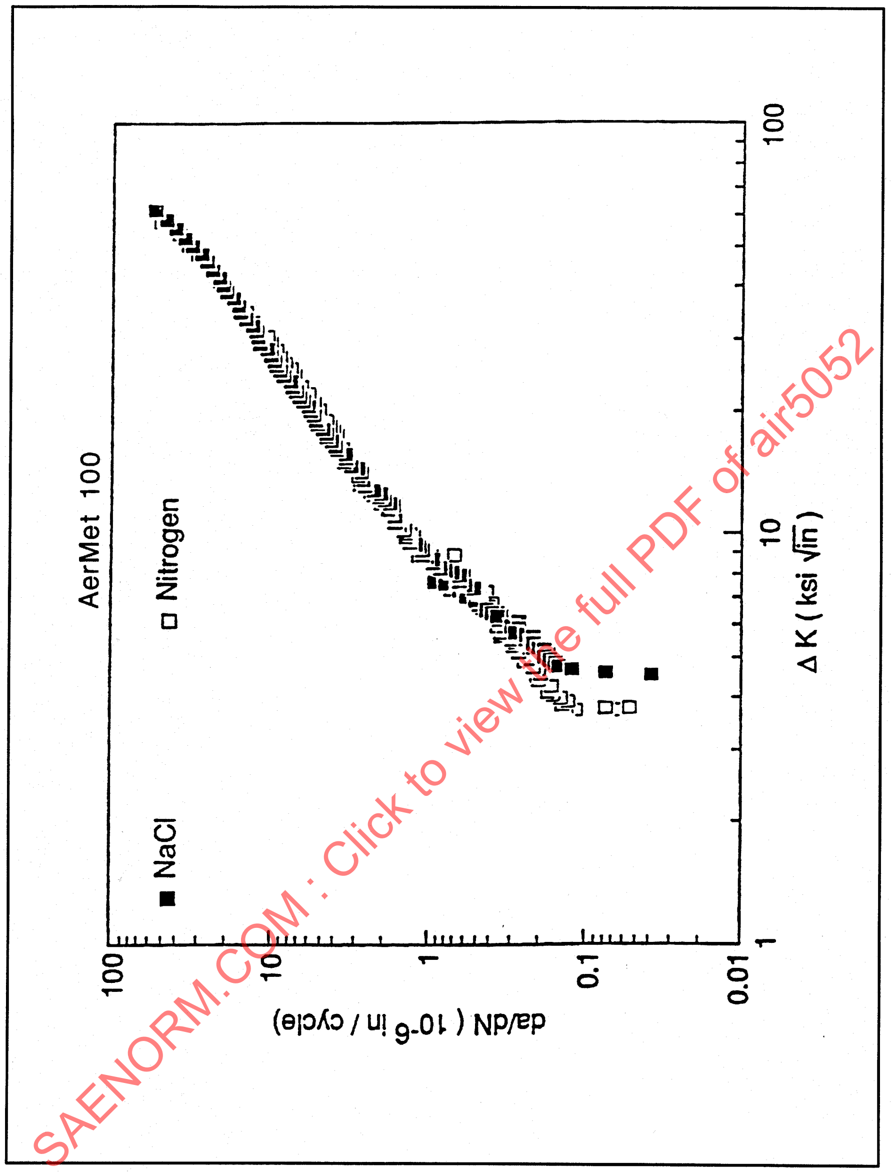

FIGURE 11 - Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for Stress Ratio R = 0.5 in Dry Nitrogen Gas and a 3.5% NaCl Solution

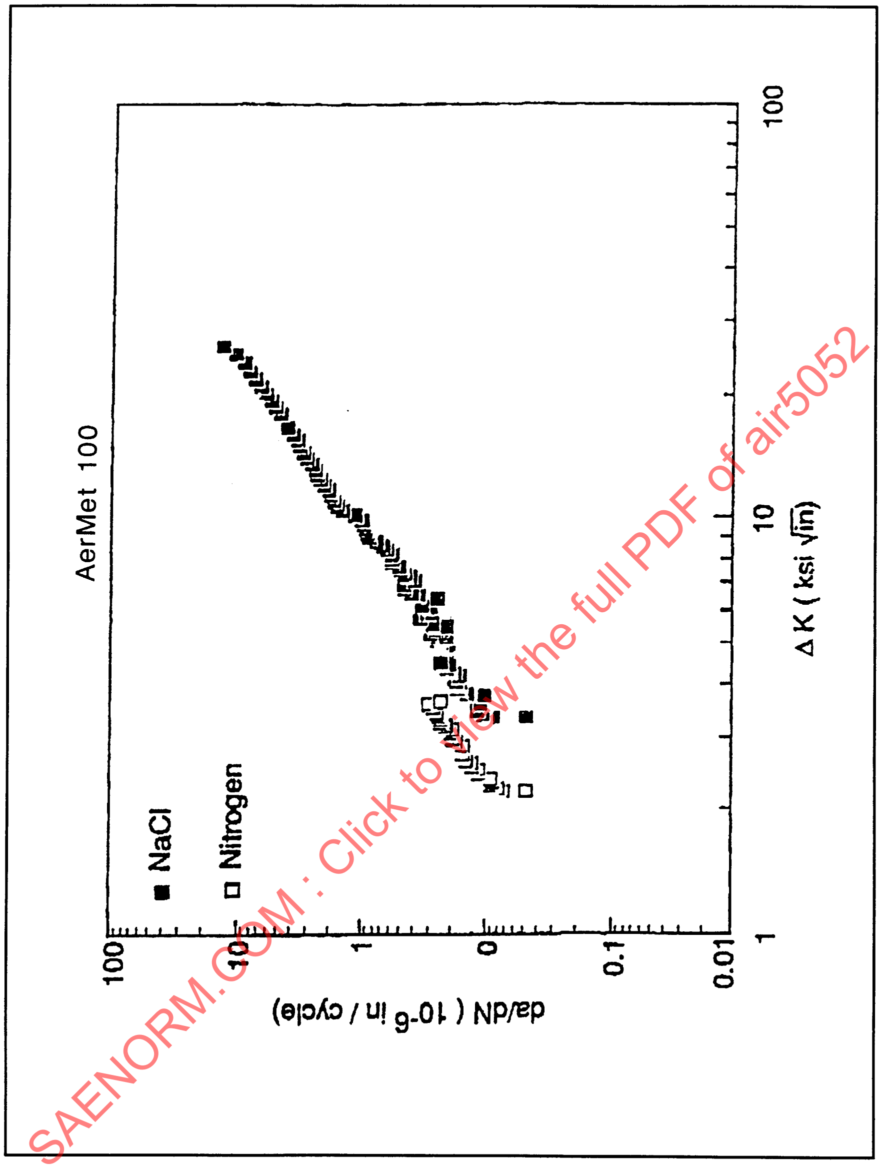

FIGURE 12 - Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for Stress Ratio R = 0.8 in Dry Nitrogen Gas and a 3.5% NaCl Solution

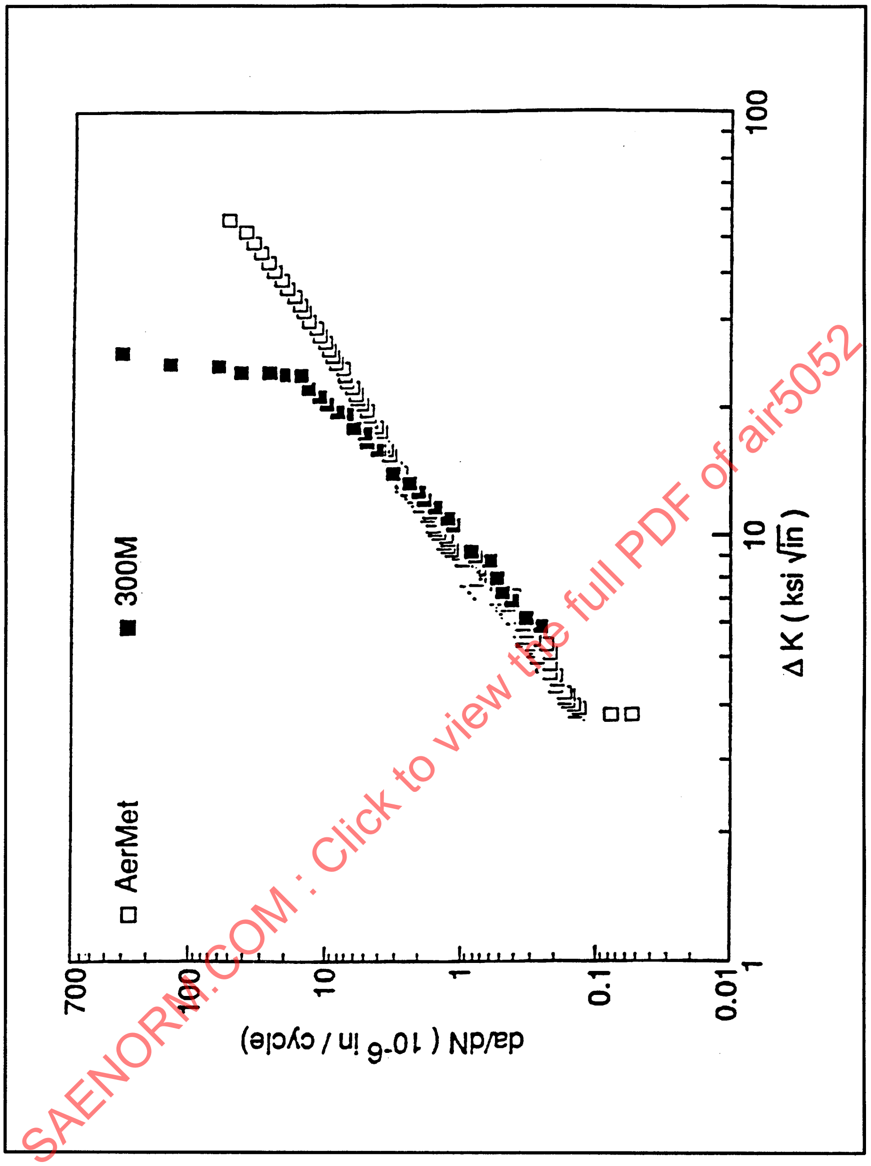

FIGURE 13 - Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for AerMet 100 and 300M Steels in Inert Environments

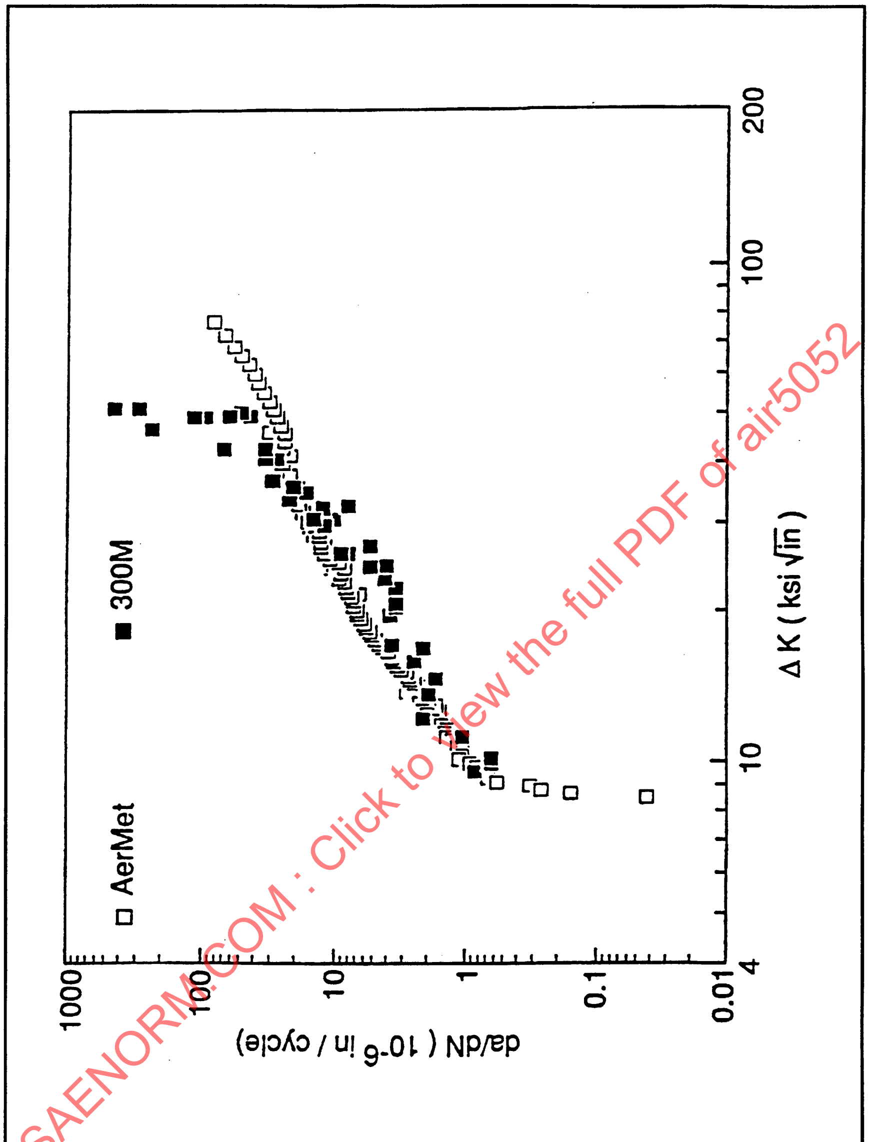

FIGURE 14 - Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for AerMet 100 and 300M Steels in Corrosive Environments

4.4 Corrosion Resistance:

The corrosion resistance of the maraging steels, due to their highly alloyed composition, is superior to that of low-alloy steels. The galvanic compatibility of maraging steels is very similar to low-alloy steel.

A study was conducted on the corrosion behavior of landing gear steels, AerMet 100, 300M, AF1410, Hy-Tuf and 4340. It included investigation of immersion corrosion in a 3.5% NaCl aqueous solution, salt spray corrosion in a fog chamber of 5% NaCl aqueous solution and humidity corrosion using distilled water. The immersion corrosion and salt spray corrosion rates of AerMet 100 are 33 to 40% and 13 to 20% those of 300M steel, respectively. In a 100% humidity chamber at 120 °F, AerMet 100 did not show any measurable corrosion within the employed test period of 110 days, whereas 300M is quite susceptible to humidity corrosion. Its rate is 2.0413 mpy (mils per year) or 0.0447 mdd (milligrams per square decimeter per day).

Figure 15 shows immersion corrosion rate expressed by the reductions in size and weight of square sheet specimens suspended in the 3.5% NaCl solution at room temperature.

Figure 16 shows the salt spray corrosion rates. As for immersion corrosion, the rate is greatest at the beginning of the exposure and decreases with time. (10)

Corrosion protection is required for AF1410 and AerMet 100 steels.

4.5 Stress Corrosion Cracking Resistance:

Ultra-high strength steels do not reach a true threshold stress intensity at 1000 hours. Long term stress corrosion cracking tests (10,000 hours or more) are required to establish stress corrosion thresholds (KIscc) for these steels.

AF1410 steel (Co-Ni) and its derivatives, 0.20C AF1410 and AerMet 100, show substantially reduced susceptibility to stress corrosion up to 1000 hours of exposure, compared to low alloy steels such as 300M, 4340 and Hy-Tuf, and maintain their advantage to a lesser extent for exposure times up to 10,000 hours. (300M steel is very susceptible to stress corrosion cracking and has a very low stress corrosion fracture toughness.) The KIscc value for 300M is 10 kis√in with 35 ksi√in for AerMet 100 and 55 ksi√in for AF1410 at comparable strength levels. (1) (4)

Highest SCC resistance is associated with the ultra-high strength steels with low carbon, lath martensite microstructures, with fine M_2C type carbides.

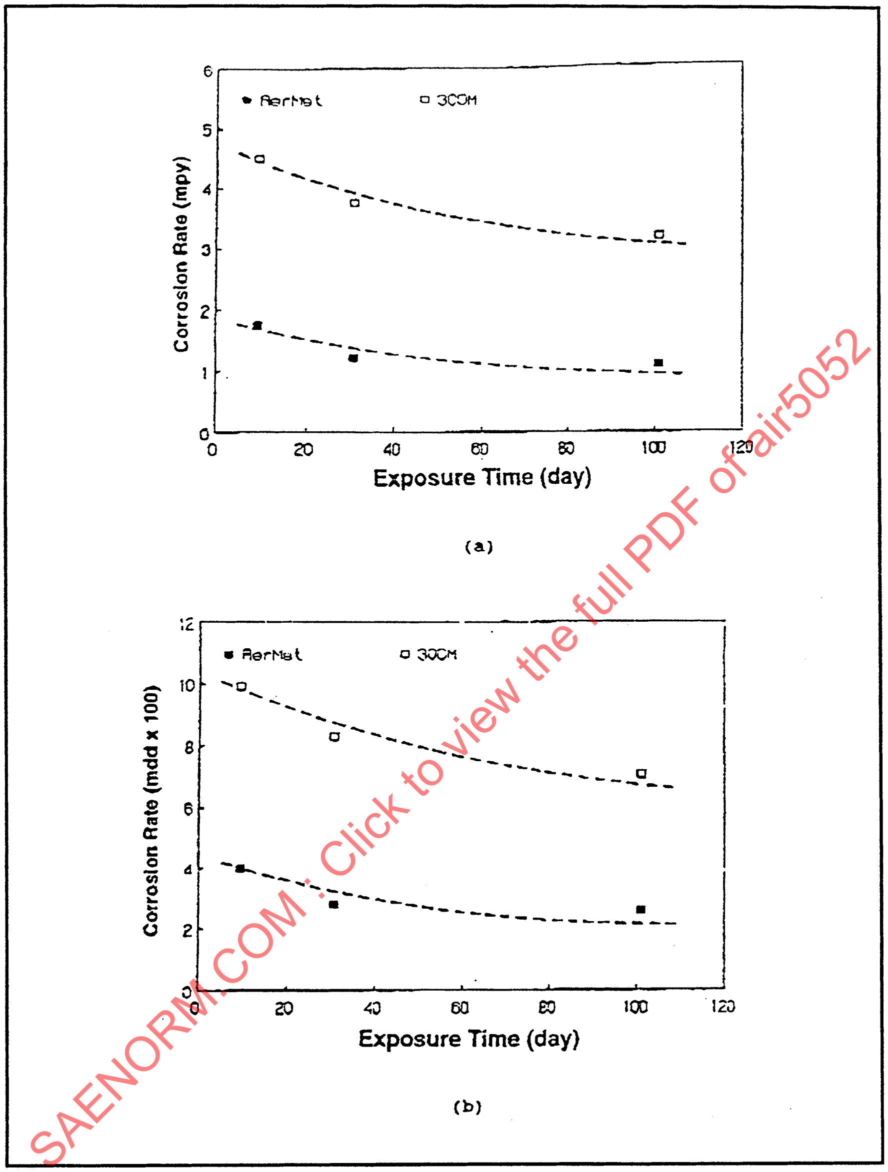

FIGURE 15 - Immersion Corrosion Rates of AerMet 100 Steel and 300 Steels
(a) Size Reduction Rate, (b) Weight Reduction Rate,
(mpy: mils per year, mdd: milligrams per square decimeter per day)

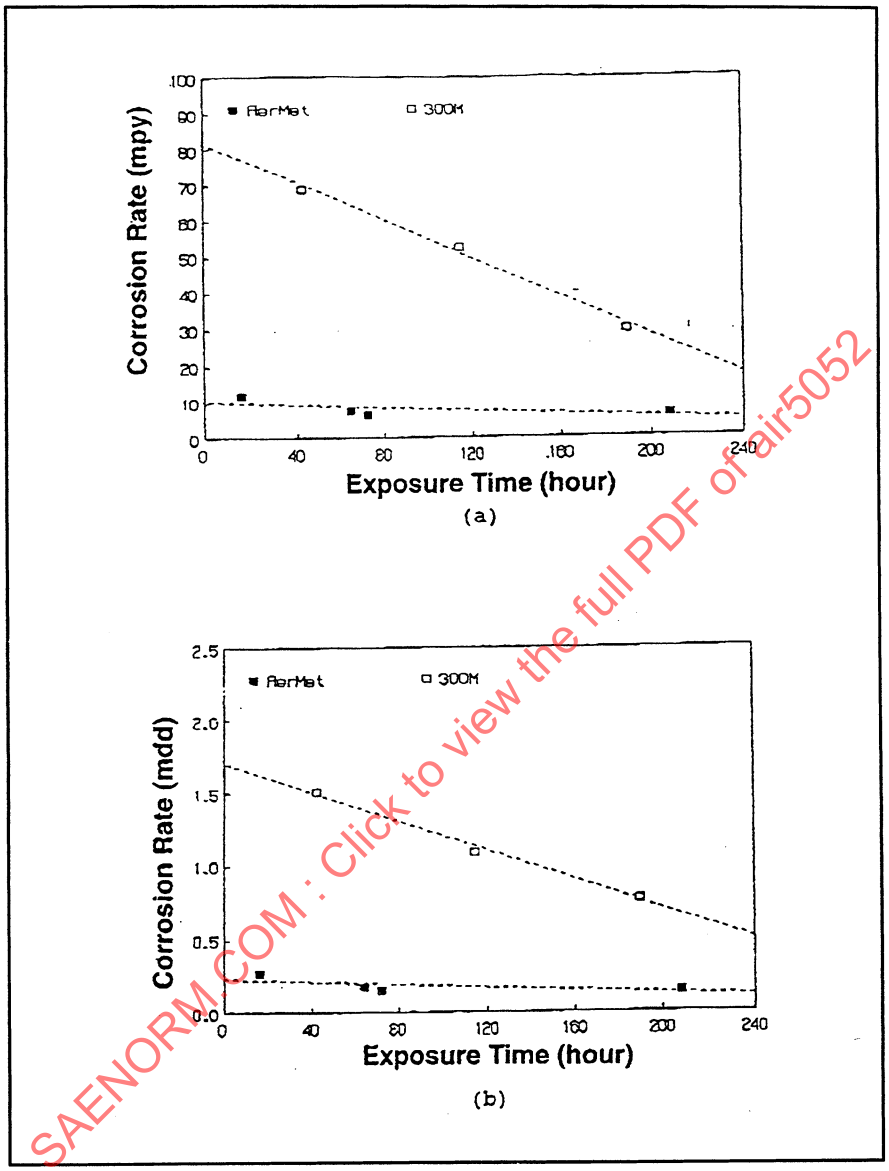

FIGURE 16 - Salt Spray Corrosion Rates of AerMet 100 Steel and 300M Steel
(a) Size Reduction Rate, (b) Weight Reduction Rate

4.6 Temperature Capabilities:

The upper boundary of temperature limitations for low-alloy steels is determined by their tempering temperatures. This is 525 to 625 °F for 300M at the 280 to 300 ksi strength level (3). The maraging steels, because their hardening mechanism is much different than quench and tempered steels, can withstand 700 °F for 3000 hours (3). The low temperature boundary for low-alloy steels is the ductile to brittle transition temperature. This is approximately -100 °F for 300M. At this time, available data indicates no ductile to brittle transition for either AF1410 or AerMet 100 at -60 °F.

The effect of temperature on coatings will vary widely depending on the coating. Diffused nickel-cadmium can operate in service up to 900 °F while ion vapor deposited aluminum coatings are good to 925 °F.

The higher temperature capability of the maraging steels could benefit aircraft brake design if it results in higher axle temperature limits. Axle temperature limitation is usually a design driver for brakes, especially carbon brakes that operate at higher temperatures. Axle temperature limits cause compromises in design, performance and cost. For example: heavier heat sinks, composite axle bushings, axle heat shields, and increased cooling times.

4.7 Embrittlement:

300M steel at high strength levels is susceptible to hydrogen embrittlement, tempered martensite embrittlement, and liquid metal embrittlement (3). The resistance of AerMet 100 steel to hydrogen embrittlement is superior to that of 300M steel. This is based on hydrogen embrittlement testing: Specimens of AerMet 100 and 300M steels were electrochemically charged then bright cadmium plated to prevent egress of hydrogen. Tensile tests were conducted at three strain rates and the hydrogen embrittlement susceptibility was measured by losses in ultimate tensile and yield strengths, percent elongation and percent reduction in area. Fractographic comparisons were made between as-received and hydrogen-charged specimens to determine changes in failure mechanisms. (10)

In the uncharged steels, the mechanical properties did not vary significantly with strain rate. The 24 hour electrochemical charging deteriorated the properties of both steels. The ductility and strength of the 300M steel dropped off rapidly even at the highest strain rate. No ductility remained at the lowest strain rate. The strength of AerMet 100 did not significantly decrease with decreasing strain rate. (10)

The fractographic examination showed an intergranular fracture initiation site for the hydrogen-charged 300M steel. The AerMet 100 steel did not exhibit any intergranular fracture. However, its fracture surface morphology became more brittle in appearance, and indicated the specimen was not completely saturated with hydrogen. This indicates the diffusivity of hydrogen in AerMet 100 steel is lower than in 300M steel. (10)

It is recommended that processes appropriate to ultra high strength materials be used with circa 260 ksi maraging steels.

4.8 Reduced Aging Temperature Properties:

875 °F Aged: Comparison of properties for 875 °F (5 h) age AerMet 100 versus standard age [900 °F (5 h)] AerMet 100 versus 300M yields the following conclusions: (See Figures 17 through 24).

Compared with standard aged AerMet 100, 875 °F aged AerMet 100 has 5% higher ultimate tensile strength, 5% higher yield strength, 20% lower fracture toughness, 12% lower elongation, 5% lower reduction in area, 7% higher compressive yield strength, 9% higher ultimate shear strength, and 5% higher bearing yield and ultimate strengths.

Compared with 300M, 875 °F aged AerMet 100 has 5% higher ultimate tensile strength, 5% higher yield strength, 90% higher fracture toughness, 77% higher elongation, 155% higher reduction in area, 14% higher compressive yield strength and 9% higher ultimate shear strength. (9)

4.9 Aging Time:

Aging time is critical for AerMet 100. The ultimate tensile strength is lower than 280 ksi if it is aged at 900 °F for more than 6 hours. The retention of a compressive residual stress after long time exposure at aging temperature is questionable.

5. PROCESSABILITY:

5.1 Forging:

Carpenter Technology Corp. conducted forging studies on AerMet 100 in conjunction with Ladish Forge on the B757 lower side strut and B747 main gear upper strut; with Shultz Steel on the A-12 launch bar; and with Park Drop Forge/Bendix on the A-12 main gear piston, shock strut.

The B757 lower side strut was readily forged from a temperature of 1800 °F. Mechanical properties of the forging met requirements of AMS 6532 and equaled or exceeded the billet. Scale formation appeared less severe than in 300M.

Quality B747 upper strut forgings were obtained using forging temperatures similar to 300M with mechanical properties equal to or exceeding the minimum requirements of AMS 6532. Scale formation appeared less severe than in 300M.

A-12 launch bar forgings were readily forged within a temperature range of 1650 to 2050 °F. A forging temperature of 1850 °F appeared to provide the optimum combination of mechanical properties, grain size and depth of scale penetration and decarburization. Mechanical properties equaled or exceeded the minimum requirements of AMS 6532. It was suggested that AerMet 100 forgings be normalized.

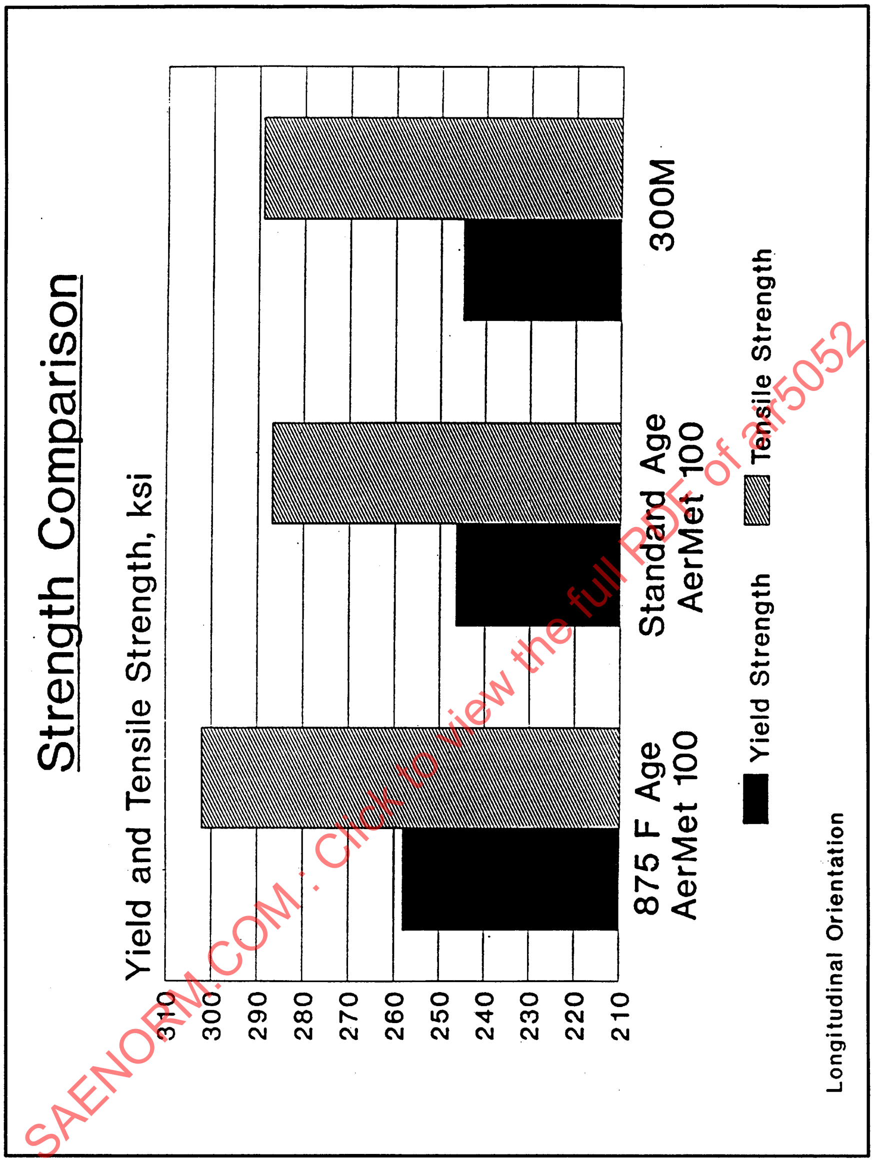

FIGURE 17 - Strength Comparison

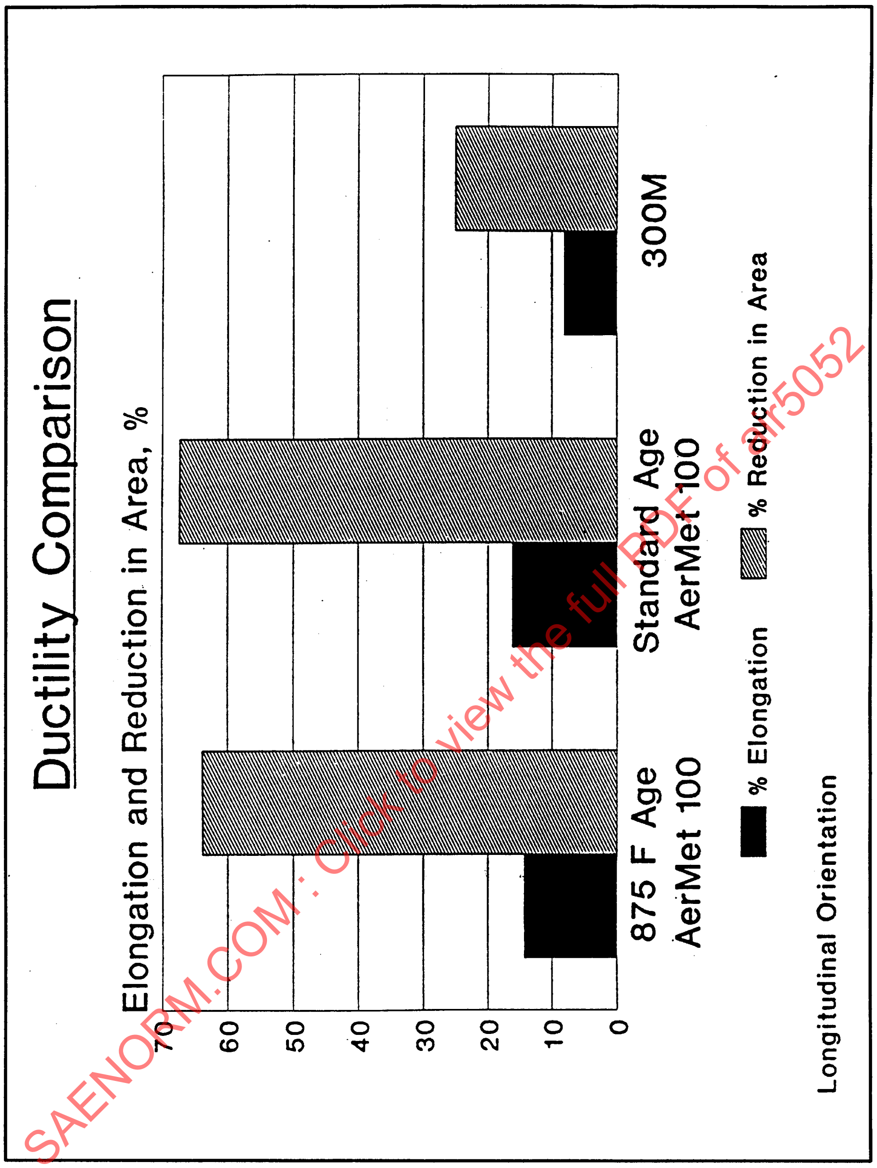

FIGURE 18 - Ductility Comparison

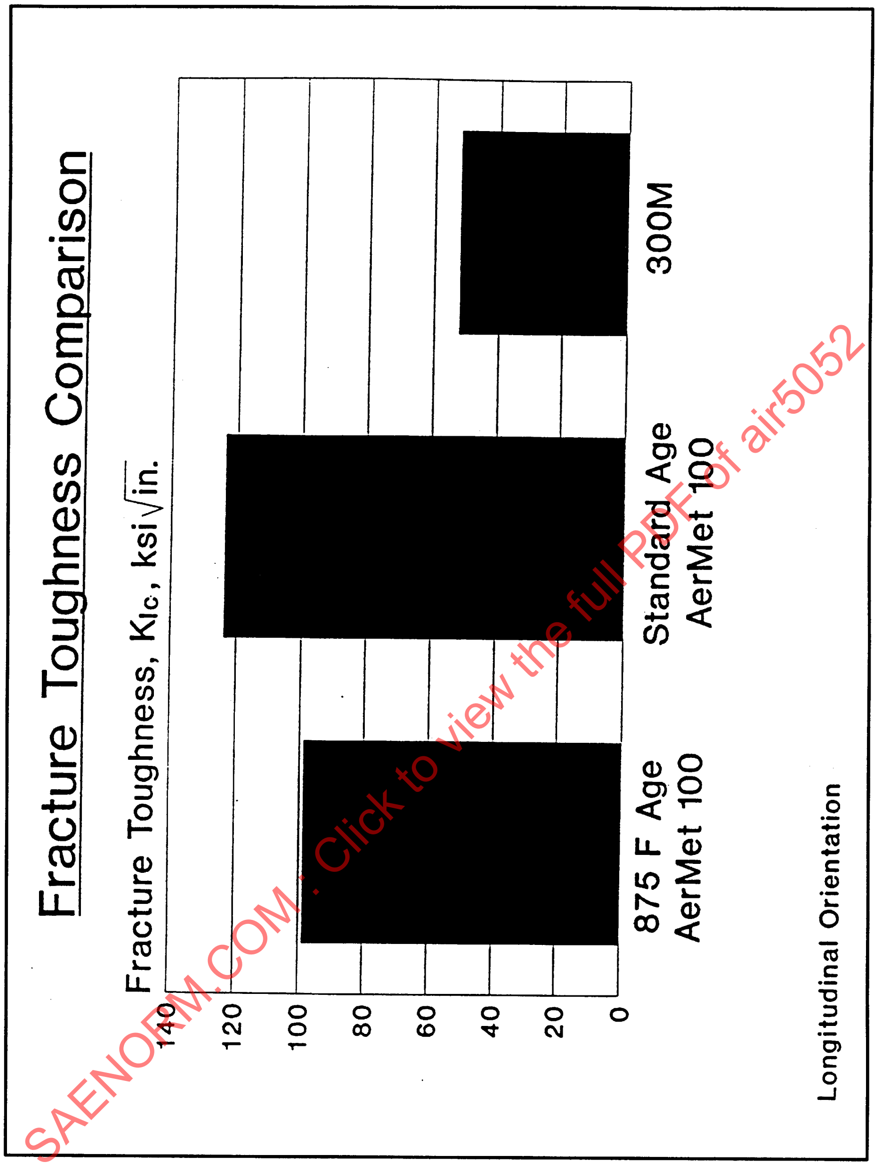

FIGURE 19 - Fracture Toughness Comparison

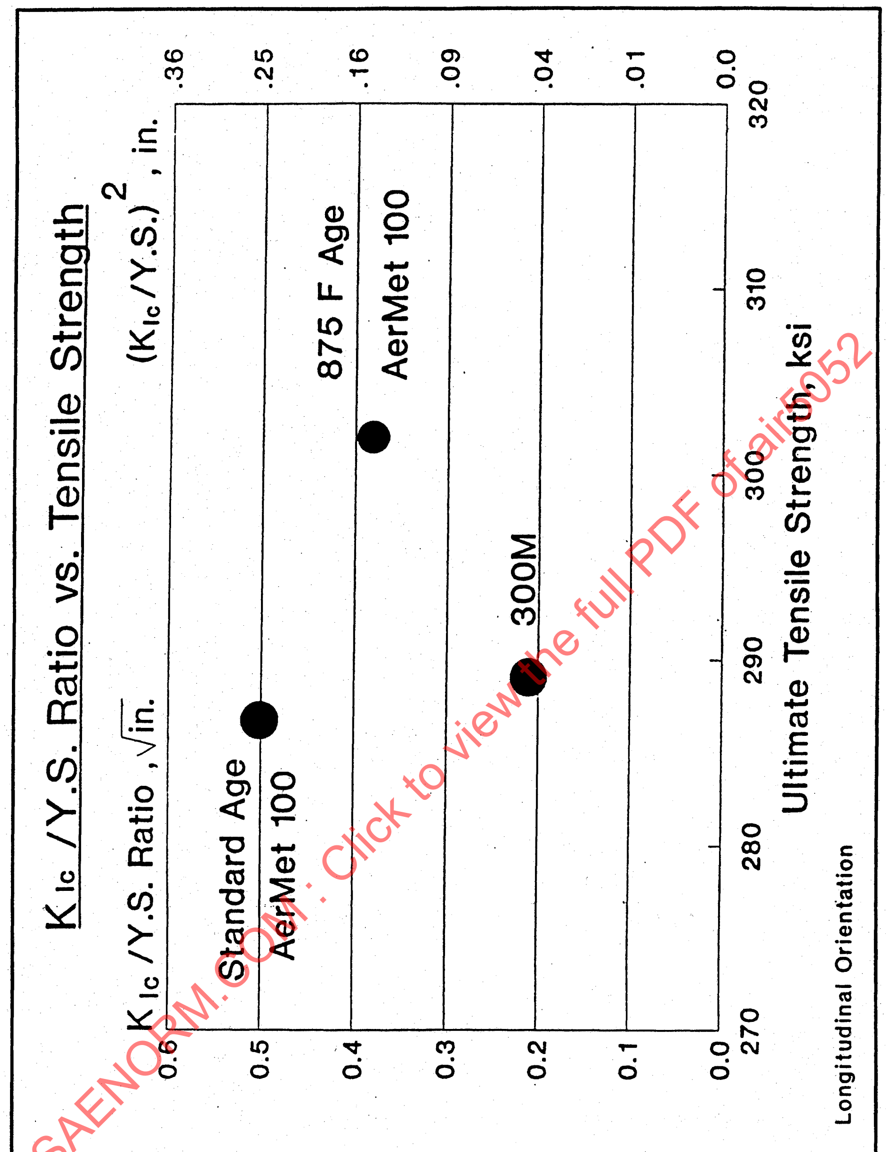

FIGURE 20 - K_{Ic}/Y.S. Ratio Versus Tensile Strength

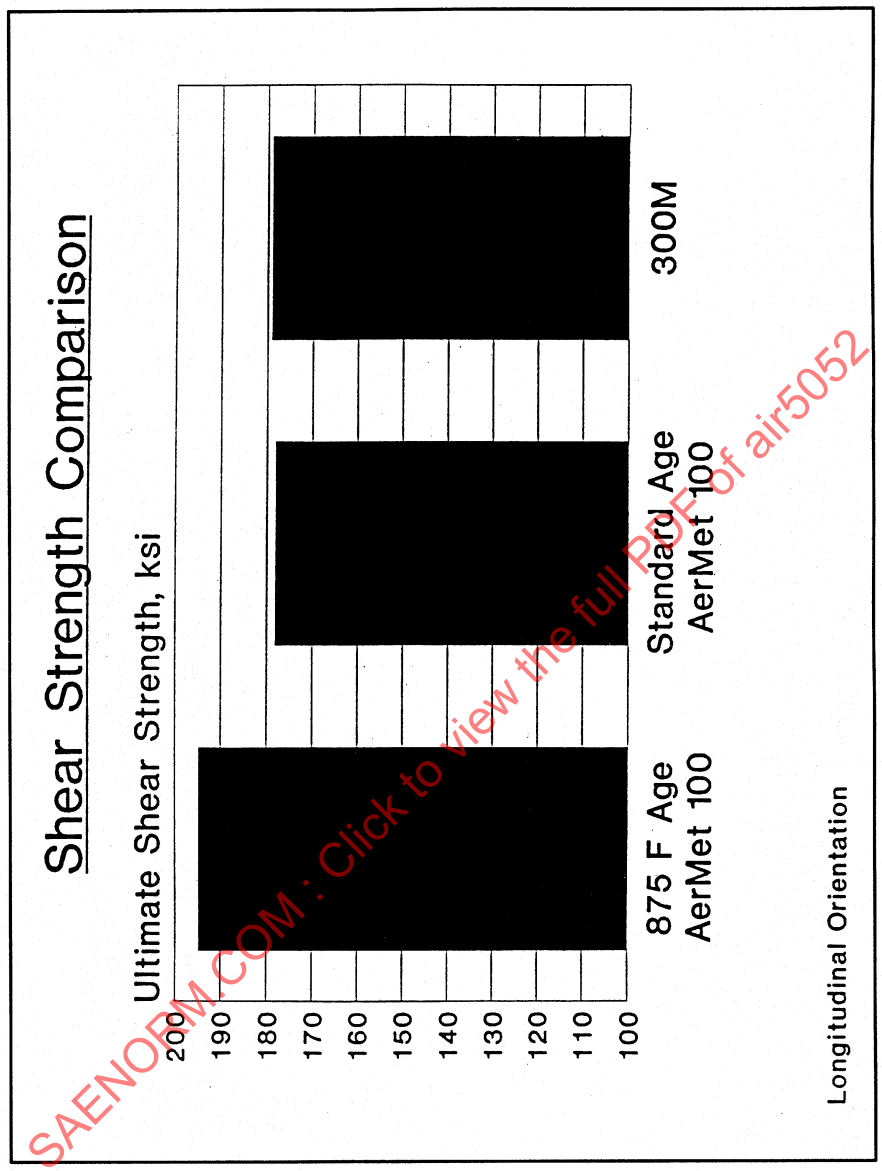

FIGURE 21 - Shear Strength Comparison

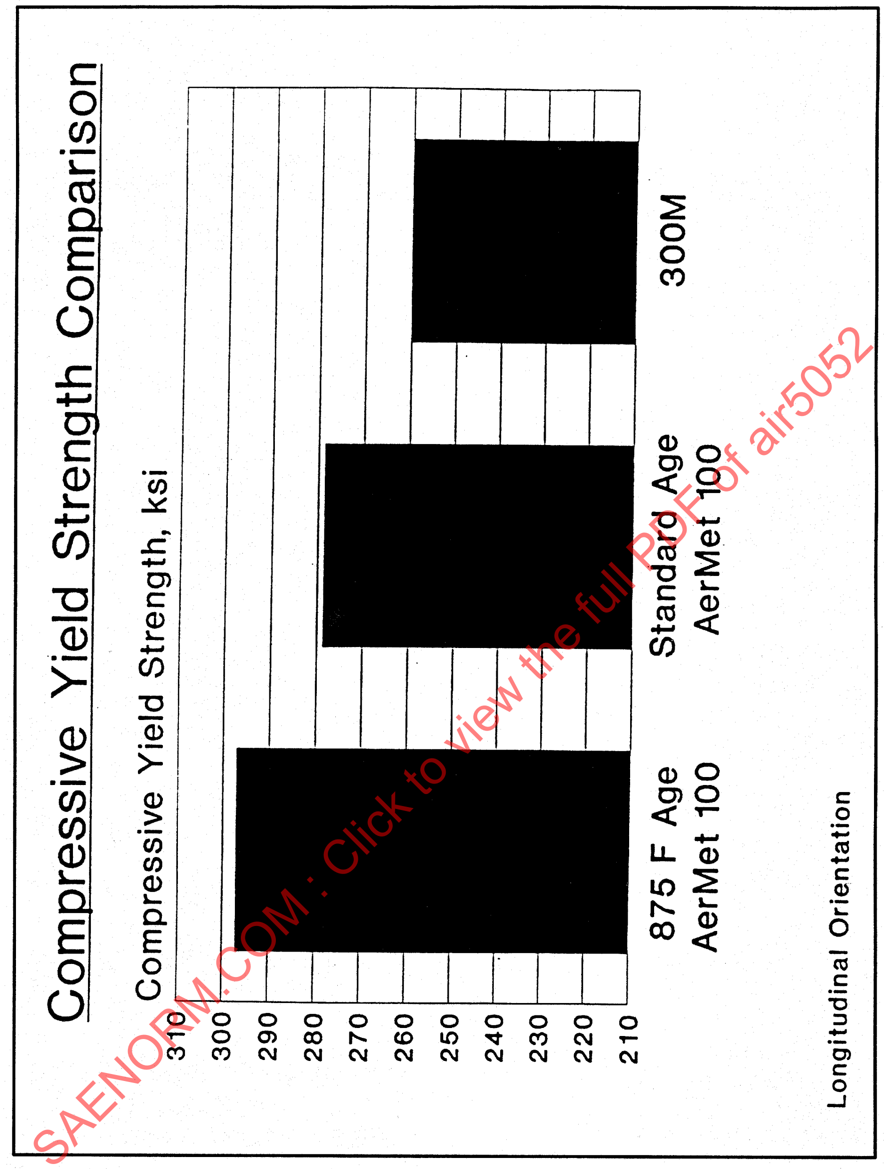

FIGURE 22 - Compressive Yield Strength Comparison