Technical Report on Material Toughness

API 6AM
SECOND EDITION, SEPTEMBER 1, 1995
(FORMERLY BULLETIN 6AM)

American Petroleum Institute
1220 L Street, Northwest
Washington, DC. 20005

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Exploration and Production Department

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FOREWORD

This technical report is under the jurisdiction of the API Subcommittee on Valves and Wellhead Equipment. It is a report of the methodology and conclusions of a task group study of material toughness requirements for equipment covered by API Specification 6A, *Specification for Wellhead and Christmas Tree Equipment.* The report was first issued as API Bulletin 6AM, First Edition, September 1, 1989, and was reaffirmed and reissued in 1995 as a technical report designated API 6 AM.

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SUMMARY

CVN toughness requirements can be used as a quality assurance measure in API Specification 6A equipment to screen materials with poor notch toughness. This should help to minimize brittle fracture of wellhead and of christmas tree equipment in the field.

A minimum average of 15 ft-lb is justified in API Specification 6A for all temperature classifications of all PSL levels of equipment. This does not preclude the use of the current lateral expansion requirements for PSL level 4 equipment. The Task Group recommends 20 ft-lb. This compromise required that the Task Group stipulate 15 ft-lb in the ***transverse** direction:* in order to satisfy logic that required 15 ft-lb in the transverse direction, a longitudinal "equivalent" was necessary.

Additional work is required to establish brittle fracture criterion for API Specification 6A materials using Charpy-fracture mechanics correlations.

Technical Report on Material Toughness

1 Scope

1.1 INITIAL TASK GROUP CHARGE

The July 30, 1986, API Subcommittee Meeting Minutes contained the Material Toughness Task Group Charge. It comprised Attachment 6. The charge(s) were:

1. Evaluate the material toughness requirements for API Specification 6A materials, for acceptance worldwide.
2. Perform a survey of the industry and review literature for material toughness values based on technical data and design requirements.
3. Devise a method or action to resolve difference between the European and U.S. opinions on material toughness.
4. Establish work groups to prepare appropriate revisions to API Specification 6A for ballot by June 1987.

1.2 AMENDEDTASK GROUP CHARGE

The Task Group came to several conclusions based on the charges:

Charge 1: The Task Group could not evaluate worldwide parameters necessary for acceptance of API Specification 6A materials toughness requirements. The justification for other groups' requirements was not readily obvious.
Charge 2: The members of the Task Group comprised a cross section of industry users and manufacturers which have worldwide exposure. The Task Group could not document any materials related failures on equipment whose materials had met the API Specification 6A requirement of 15 ft-lb. All documentable failures did not meet the existing requirements. A literature survey revealed no technical data or design requirements which are relatable to API Specification 6A equipment design or usage.
Charge 3: The differences between U.S. and European opinions on material toughness relate directly to a difference in philosophy. There are several differences, but the major difference is that the Europeans feel that the Charpy value relates to design while the U.S. opinion is that the Charpy test is a quality assurance exercise in sorting out "rogue materials." All other differences stem from that major premise.

Unfortunately, the technical justification of either of the requirements is unclear. The historical evidence indicates that both approaches are conservative since no API Specification 6A equipment failures have been attributed to brittle materials which met the requirements of the existing standards.

Therefore, the Task Group decided to start with a clean sheet and adopted the charge to "Determine what is necessary to prevent brittle fracture in the field."

Charge 4: With this charge in mind, the Task Group established work groups for:

a. Literature survey.
b. Literature evaluation.
c. Correlations and calculations.
d. Position paper containing proposed changes.

2 General History of API 6A/6D Activities Relative to Impact Testing of Materials

2.1 About 1969170, at the API meeting in Los Angeles, a committee was set up to review the materials listed in API Specification 6A and Specification 6D for low temperature service. This interest was generated by the activities of the Alaska Pipeline Project.

2.2 The directions given by API committees were to review the materials listed in API Specification 6A and Specification 6D and to remove those materials which would not meet the standard Charpy V notch requirements of 15 ft-lb average, none less than 12 ft-lb at -20" F. The -20" F temperature was selected simply because that was the low end of the temperature range for API products at that time. In reviewing these materials, it became very apparent to the committee members that most of the materials listed would not meet the standard Charpy requirements at -20" F and that some of the materials were even questionable above +32° F.

With this in mind, a call was put forth to all API members to report and document, if possible, any failures of API equipment which could be attributed to low notch toughness. No such failures were reported even in the Canadian or North Sea sectors. Since no failures were reported, and since it was well known that impact test values are generally considered relative in nature and are not used as a design tool, the committee was put in a quandary as to what action should be taken. There was considerable discussion on how the industry would react to removing a material from the API specifications which had been used very successfully for twenty or thirty years with no reported problems. and at the same time, support its existence and continued use in the field.

2.3 The final decision was to leave the need for impact testing at temperatures above –20° F up to the users, who could request impact testing at any temperature and stipulate any values they desired.

Equipment below -20" F would automatically require impact testing. The test temperature and energy requirements have changed somewhat over the years and have eventually evolved into the requirements of the current API Specification 6A and Specification 6D.

3 Materials Toughness Task Group History

3.1 API Specification 6A, Fifteenth Edition, was issued in April 1986. There was immediate comment from Europe, specifically Great Britain and Norway, that their concerns had been ignored and that API Specification 6A equipment was inadequate for North Sea service. Three main areas of disagreement surfaced:

- Impact energy value.
- Omission of a temperature rating specific to North Sea.
- No requirement for impact testing at service temperatures above -20" F.

These contentions arose despite the 15th Edition's new, more stringent NDE requirements which reduce flaw size acceptance and, therefore, reduce a material's ability to generate a propagating crack.

3.2 The committee was informed that the 15 ft-lb value attached to Charpy Impact Testing was the most troublesome item. This value was added to API Specification 6A in 1969 to cull materials destined for Arctic service. The 1969 Task Group's minutes indicate that they chose 15 ft-lb because ASTM A350 and A352 listed this value for the most common forging and casting materials of that time. Furthermore, the 1969 version of A320 Gr L7M bolting required 15 ft-lb. Apparently, ASTM acquired the value from the Liberty Ship work of World War II. It was thought that 15 ft-lb indicated the onset of brittle behavior in ferrous metals; that is, less than 15 ft-lb values indicate brittle behavior and greater than 15 ft-lb indicate ductile behavior.

The 1969 Task Group did not consider the effects of heat treatment, chemical content or processing. ASTM A370 states that the Charpy test is a Quality Assurance test and that the resulting value has no engineering meaning.

3.3 Since 1969 the committee has desired to gain a greater understanding of brittle failure. The study of Fracture Mechanics has been explored for oil field application. In the interest of cost the Charpy Test was seen to be the bridge between expensive Fracture Mechanics testing and a practical production means for determining acceptability of a product in a brittle fracture resistant manner. To date, there is not a universally acceptable, single conversion factor to correlate between fracture mechanics data and Charpy test results, for API Specification 6A materials.

3.4 The Europeans began using 3 1 ft-lb (42 joules) as the minimum value acceptable for materials in North Sea service. The test temperatures and the acceptance value varies so that it has been difficult to determine the source of the value. Naturally, those who use the 31 ft-lb **value** feel that those who still use 15 ft-lb may be underdesigning. The Europeans have attached Fracture Mechanics significance to the Charpy and, therefore, feel that the value has a direct correlation to how the product will perform. API Specification 6A has used the Charpy value to separate "rogue" materials from the properly processed materials. It is also clear that minimum requirements based on genera1 Fracture Mechanics studies may not be valid. By assumption and choice of equation variables, either 15 ft-lb or 3 1 ft-lb can be shown to be "acceptable."

4 API Specification 6A, Fifteenth Edition-Brittle Fracture Prevention Benefits

4.1 GENERAL

The purpose of this section is to make clear, by description and reference to API Specification 6A, Fifteenth Edition, those additional (new) Quality Assurance/Quality Control requirements that will reduce the likelihood of brittle failure, independent of toughness testing specific materials.

4.2 DESIGN CONSIDERATIONS NOW REQUIRED

a. For PSL l-4 only, the design shall take into account the effect of pressure containment and other pressure-induced loads. Specialized conditions shall also be considered, such as pressure rating changes in crossover flanges and pressurizing with temporary test plugs. (Refer to Section III, B. 1.c. of API Specification 6A, Fifteenth Edition.)
b. For PSL l-4 only, the design shall take into account the effects of temperature gradients and cycles on the metallic and non-metallic parts of the equipment. (Refer to Section III, B.2.b.(2))
c. For PSL l-4 only, the design shall take into account the effects of retained fluid on the metallic parts of the equipment. (Refer to Section III, B.3b.)

4.3 DESIGN METHODS NOW REQUIRED

a. For PSL l-4 only, specific limits for stress on all bodies and portions of equipment where dimensions are not established by the API Spec. (Refer to Section III.C.3.a., b., c., and d.)
b. For PSL l-4 only, design documentation, design review and design verification must be performed and on file. (Refer to Section III. E., F., and G.)

4.4 MATERIALS REQUIREMENTS NOW INCLUDED

For PSL l-4 only, written material specifications which specify allowable melting practices, required forming practices, specific steps of heat treatment, material chemistry limits and QTC requirements. (Refer to Section V. B., SEC. V. D.3.a. and b., SEC. V. D.4.a., b., and c., SEC. V. F. and G.)

4.5 COMPREHENSIVE WELDING REQUIREMENTS HAVE BEEN ESTABLISHED

a. For PSL l-4 only, weld joint design. (Refer to Section VI.F.1.a and Appendix E.)
b. For PSL 1-4 only, welding consumables shall conform to industry or manufacturers specified requirements. (Refer to Section VI. d.1.B (1) and (2)).
c. For PSL l-4 only, welding procedure qualification must be performed with specific requirements starting with PSL 1 and requirements increasing through PSL 3, for PSL 4 no welding is permitted except for overlay. (Refer to Section VI entirely).

4.6 IMPORTANT NEW QUALITY CONTROL REQUIREMENTS HAVE BEEN ADDED

a. For PSL l-4 only, Quality Control Personnel (inspectors) must be qualified. (Refer to Section VII. D.)
b. For PSL l-4 only, equipment used for all measurement and evaluation must be calibrated. (Refer to Section VII. D.)
c. For PSL I-4 only, hardness testing is required which serves to confirm heat treating on most commonly used materials. (Refer to Section VII. E.2.B. (3) FOR PSL 1 and additionally in SEC. VII. for higher PSL levels.)
d. For PSL 1-4 only, visual and non-destructive testing is required. Brittle failure is related to flaw size and as PSL levels increase, inspections required become more sensitive and acceptable flaw sizes allowed are smaller. (Refer to Section VII. through E.6.b(6).

4.7 Hydrostatic testing, at higher PSL levels, now has increased hold times. (Refer to Section VII. E. 8f. (4))

4.8 Manufacturing records are now called for throughout the API Specification 6A.

4.9 In the event API Specification 6A products are made by an API licensed manufacturer, they must all, regardless of PSL level, be manufactured and tested under a comprehensive quality program in compliance with API Specification Q1. (REF. API Specification Q1, Specification for Quality Programs, this applies only when the product actually bears the API monogram, now followed with the manufacturer's license number.)

5 Analysis

5.1 APPROACH

The Task Group began with a review of the literature and of service experience in order to justify the CVN requirements used in API Specification 6A. To this end, the charge of the Task Group was modified. The objective was to "prevent brittle fracture in the field."

Two approaches can be adopted in API Specification 6A to achieve this objective.

1. The CVN test can be used to provide a measure of quality assurance. In this approach, a single CVN value is specitied for screening out materials of poor quality with unacceptably low notch toughness. This single CVN value is independent of equipment design or configuration.
2. A minimum of CVN value can be specified for a given equipment design based on a fitness-for-purpose analysis. This requires the use of fracture mechanics to determine a minimum notch toughness for a given crack size to prevent brittle fracture. This minimum toughness is then converted to a CVN requirement using a KIC-CVN correlation based on comparing laboratory data from fracture mechanics specimens to CVN specimens.

The purpose of this document is to provide the basis for the Task Group's position regarding the approach, and conclusions for CVN toughness requirements that should be adopted for API Specification 6A materials.

5.2 THE USE OF CVN REQUIREMENTS IN MATERIALS SPECIFICATIONS

5.2.1 Historical Background

The use of the CVN test in material specifications has been a topic of continuing interest and controversy for many years.

The concept of using a single value of 1.5 ft-lb to prevent brittle fracture was first arrived at by the National Bureau of Standards (NBS) after a careful study of the brittle fractures in Liberty-type ships in the 1940s (2). Statistical analyses of CVN values from the origin (source), propagation (through), and arrest (end) areas of fractures from approximately 100 fractured ships provided the 15 ft-lb transition temperature criteria that was adopted for acceptance. Reference 2 additionally states:

> "Fortunately, for the engineering profession and the profession and the general public safety, similar statistical correlations between test results and service failures do not exist for any other class of structures because there have not been such a large number of failures in any type of structure. However, the difficulty of obtaining service experience creates a problem for the design engineer in establishing toughness criteria for new types of structure."

Therein lies the difficulty in extending 15 ft-lb to API Specification 6A equipment. Still, API adopted the 15 ft-lb requirement for low temperatures (below -20" F) in 1970. The transition temperature criteria of the NBS had been replaced with a single minimum CVN toughness acceptance value.

To date, there have been no reported field failures by brittle fracture of either christmas tree or wellhead equipment which meet the 1.5 ft-lb requirement. Reported field failures have exhibited leak-before-break behavior associated with casting defects (interconnected shrinkage cavities) (3). A brittle failure of a head casting during shop by hydrotest was traced to poor design and inadequate inspection: interestingly this failure was associated with CVN values in excess of 3 1 ft-lb (4). This failure is not a failure of API Specification 6A equipment.

5.2.2 Quality Assurance

The CVN test has been successfully used in API Specification 6A to screen materials with low notch toughness. There is general agreement in the literature that the CVN test is valuable as a control of material quality by sorting out rogue materials from those with good notch toughnes (4, 5, 6).

The ASME Sect. VIII Divs. 1 and 2 Codes have successfully used the CVN test to minimize brittle fracture of pressure vessels in field service. These Codes require minimum CVN toughness values, which may vary according to the material and its thickness. ASME has been able to specify more than a single CVN value because of extensive field experience and detailed materials specifications.

5.2.3 Fitness-For-Purpose Analyses

There is considerable disagreement on the suitability of the CVN test for use in a fitness-for-purpose analysis. A major obstacle is finding a suitable fracture toughness-CVN correlation to relate required fracture toughness to CVN values. Most investigations have found that these correlations are material sensitive and apply only for certain materials in limited strength ranges (7, 8, 9, 10, 11). A correlation derived by laboratory CVN tests for one class of materials cannot necessarily be translated to another.

Use of a fitness-for-purpose analysis requires a substantial amount of supporting documentation, including materials specifications, realistic stress analyses and flaw growth characteristics of the equipment of interest, an extensive data base of CVN toughness for each material, field experience relating performance to given CVN values, and finally, a proven toughness-CVN correlation for that material. To be most effective, only a few and preferably a single correlation is desirable.

Even with all of this information, existing correlations provide only an estimate of fracture toughness. The accuracy of toughness values derived from these correlations is questionable in some cases and is generally thought to be highly conservation (12, 13).

The conservatism inherent to specifying CVN values based on correlations was borne out in a recent study by Battelle Laboratories (14). This study involved fullscale testing of valves containing known defects The results indicated that predictions based on KIC-CVN correlations were “extremely overly conservative” and predicted failure stresses of about half the observed values. Only the J/COD technique, which involves elastic-plastic fracture mechanics, was found to provide reasonable failure stress predictions.

In recent work, Willoughby (12) has performed fitness-for-purpose analyses to determine CVN requirements for wellhead equipment for North Sea service. The analyses reanalyzed the need for 31 ft-lb min., as is currently thought to be necessary by the DNV. Willoughby utilized four KIC-CVN correlations from the literature: Barsom and Rolfe (15), Sailors and Corten (16), Marandet and Sanz (17), and Barsom (18). Calculated CVN requirements varied from 2 joules to 72 joules, depending on the defect criteria used for KIC calculation and on the correlation used. He chose a minimum requirement of 27 joules (20 ft-lb) allowing for assumptions made in the analyses. It should be emphasized that these analyses contained many conservative assumptions and that the final CVN requirement was chosen from a range of calculated values.

5.3 API 6ATASK GROUP FITNESS-FOR-PURPOSE ANALYSIS

5.3.1 Assumptions

This analysis assumes that reasonable correlations exist relating CVN toughness requirement of KIC derived by linear elastic fracture mechanics. Also, although these correlations are obtained from other than API Specification 6A materials, it is assumed they may be applied to like materials used in wellhead and christmas tree equipment. The nominal stress and defect size used to calculate KIC conform to API Specification 6A requirements.

5.3.2 Design Stress

API Specification 6A stipulates a design stress intensity at rated working pressure of 0.67 times the material minimum specified yield strength and a maximum stress intensity at hydrostatic test pressure of 0.83 times the yield strength. If distortion energy theory is invoked in design, the combined stress level is restricted to the minimum yield strength.

If one takes into account that there are local areas of stress concentrations inherent to any design, it is apparent that the attainment of yield strength stresses is reasonable for wellhead and Christmas tree equipment. However, the nominal stress in service is expected to be one-half to two-thirds of the stress in hydrostatic test. Therefore, the overall nominal stress in the equipment is not expected to exceed 0.67 times yield strength in service.

The KICs are 17.3 ksi $(in.)^{1/2}$ and 54.3 ksi $(in.)^{1/2}$ for the surface and volumetric cracks, respectively.

5.3.3 Defect Size

The defect sizes specified in API Specification 6A are dependent on the Product Specification Level (PSL). For PSL 1 no defect size limits are specified. For PSLs 2, 3, and 4 the maximum length of surface defect specified is 3/16 in. These are supplemented by restrictions on linear and a real defect distribution. For weldments, the defect size limits are more severe and are restricted to 1/8 in. for thicknesses up to 5/8 in. For thicknesses greater than 5/8 in. the defect is stretched to 3/16 in.

PSL 3 calls for restrictions on volumetric defects in the parent metal whose limits are identical to those of PSL 2 weldments.

PSL 4 stipulates that for hot worked parts the volumetric defect shall not exceed 1/4 in.

For the purposes of this report, the maximum surface defect as substantiated above will be taken to be 3/16 in. Furthermore, the defect will be assumed to be semicircular in shape (a conservative assumption) so that the depth of the defect would be 3/32 in. For volumetric defects, the length of the defect is taken to be 3/4 in.

5.3.4 KIC-CVN Correlations

For all correlations, KIC is expressed in ksi $(in.)^{1/2}$ and CVN toughness is expressed in ft-lb.

The Maradet and Sanz (17) correlation, based on establishing temperatures at which CVN and KIC swung up in the CVN temperature transition curve, is as follows:

$$KIC = (19)*(CVN)^{1/2} \qquad \text{(Equation 2)}$$

The correlation of Equation 2 is subject to me restriction that the fracture surface is 80% crystalline. This correction applies to the brittle fracture portion of the CVN temperature curve.

$$(KIC)^2/E = (2)*(CVN)^{3/2} \qquad \text{(Equation 3)}$$

$$(KIC/SY)^2 = (5)*(CVN/SY - 0.05) \qquad \text{(Equation 4)}$$

Where:

E = Elastic modulus = 30 x 10^3 ksi
SY = Yield strength in ksi
KZC = ksi $(in.)^{1/2}$

These correlations were derived from tests of structural steels with yield strengths of 39 ksi to 246 ksi and with CVN toughness of 3 ft-lb to 89 ft-lb.

Begley and Logsdon (21) employed Equation 4 in addition to the lower shelf KIC expressed by:

$$KIC = (0.45)*SY \qquad \text{(Equation 5)}$$

The notch toughness corresponding to the transition temperature was taken as the average of KIC values given by Equations 4 and 5 and was taken to represent 50% crystalline fracture on a CVN specimen. Equation 5 represented 100% crystalline fracture and further specified a lower limit for KIC of 25 ksi $(in.)^{1/2}$.

Sailors and Corten (16) were concerned with establishing CVN requirements for A533B, a pressure vessel steel with a yield strength of 60 ksi to 70 ksi and with CVN toughness of 5 ft-lb to 50 ft-lb. The correlation pertaining to the transition temperature region was expressed as:

$$KIC = (15.5)*(CVN)^{1/2} \qquad \text{(Equation 6)}$$

5.3.5 Derivation of the CVN Toughness Requirement

Using the Equations 2 through 6 and the KICs derived earlier, the CVN toughness requirements were calculated and are summarized in Table 1. The highest CVN toughness required is 13.4 ft-lb. Therefore, a minimum average CVN toughness of 15 ft-lb should be adequate for screening rogue materials to minimize equipment field failures by unstable crack propagation.

Table 1 -CVN Values Derived by KIC-CVN Correlations (See Note)

(1)	(2)	(3)	(4)
	CVN Value Equivalent (ft-lb)[a]		
Type of Correlation	Surface Crack	Volumetric Crack	Applicable Crack
Marandet and Sanz	0.83	8.15	Lower shelf
Barsom and Rolfe	2.92	13.4	Transition
Rolfe and Novak	4.55	11.6	Upper Shelf
Begley and Logsdon	NA[b]	8.9	Transition
Sailors and Corten	1.25	12.3	Transition

Note: The above analyses assume ksi yield strength material with 50 ksi nominal stress in service.
[a]KIC = 17.2 ksi $(in.)^{1/2}$ for a semicircular surface crack.
KIC = 54.3 ksi $(in.)^{1/2}$ for a volumetric crack.
[b]Average KIC value is below that of the 100% crystalline fracture region.

5.3.6 Discussion

The calculations presented here highlight the large amount of scatter obtained using KIC-CVN correlations in fitness-for-purpose analyses. Figures 1 through 4 show an even wider range of required CVN toughness when different assumptions are made for defect size and for nominal stress in the KIC calculation. The scatter in required CVN toughness is influenced by degree of conservatism used in assumptions and by the amount of CVN and fracture mechanics data available or applicable to a given material.

Another limitation to the Task Group's analysis was that the simplest of fracture mechanics formulas was used to calculate IUC. The complex state-of-stress within the equipment was not accounted for nor were the effects of plastic deformation. A more thorough analysis should determine if JIC or crack-opening-displacement are better measures of toughness than KIC for API Specification 6A materials.

The uncertainty associated with calculated CVN toughness increases for alloys such as 13 Chrome where the published CVN data base is very small and the accuracy of existing correlations has not been verified in the laboratory.

5.3.7 Conclusions

a. Based on the defect limits set forth in API Specification 6A, Fifteenth Edition, the design stress levels assumed in the Task Group's analysis, and the available KIC-CVN correlations from the literature, the specification of 15 ft-lb minimum average CVN toughness is justifiable for API Specification 6A equipment. This CVN toughness should be used as a quality assurance measure to screen rogue materials. It should be noted that the 15 ft-lb CVN toughness is supported by field experience of API Specification 6A wellheads and christmas trees. Not a single brittle fracture in the field has been reported.

b. More CVN toughness data is needed for API Specification 6A materials, particularly for corrosion resistant alloys such as 13 Chrome. Once these data are available, better KIC-CVN correlations may be developed and different criteria to prevent brittle fracture may have to be included in API Specification 6A.

c. Further development of the fracture mechanics analysis of wellheads and Christmas trees is needed before CVN toughness may be properly calculated using a fitness-for-purpose analysis. This more detailed fracture mechanics analysis was beyond the scope of the Task Group's current charge.

d. In the Fifteenth Edition of API Specification 6A, CVN toughness testing is required for only the lower temperature classifications of PSL l-3 equipment. Testing is required for all temperature classifications of PSL 4, with a required minimum lateral expansion of 0.015 in. The Task Group's analysis, as summarized in 5.3.7a, 5.3.7b, and 5.3.7c above, suggests that a minimum average CVN toughness of 15 ft-lb is justifiable for all temperature classifications, regardless of PSL level. This does not preclude the additional requirement of lateral expansion of PSL 4 equipment.

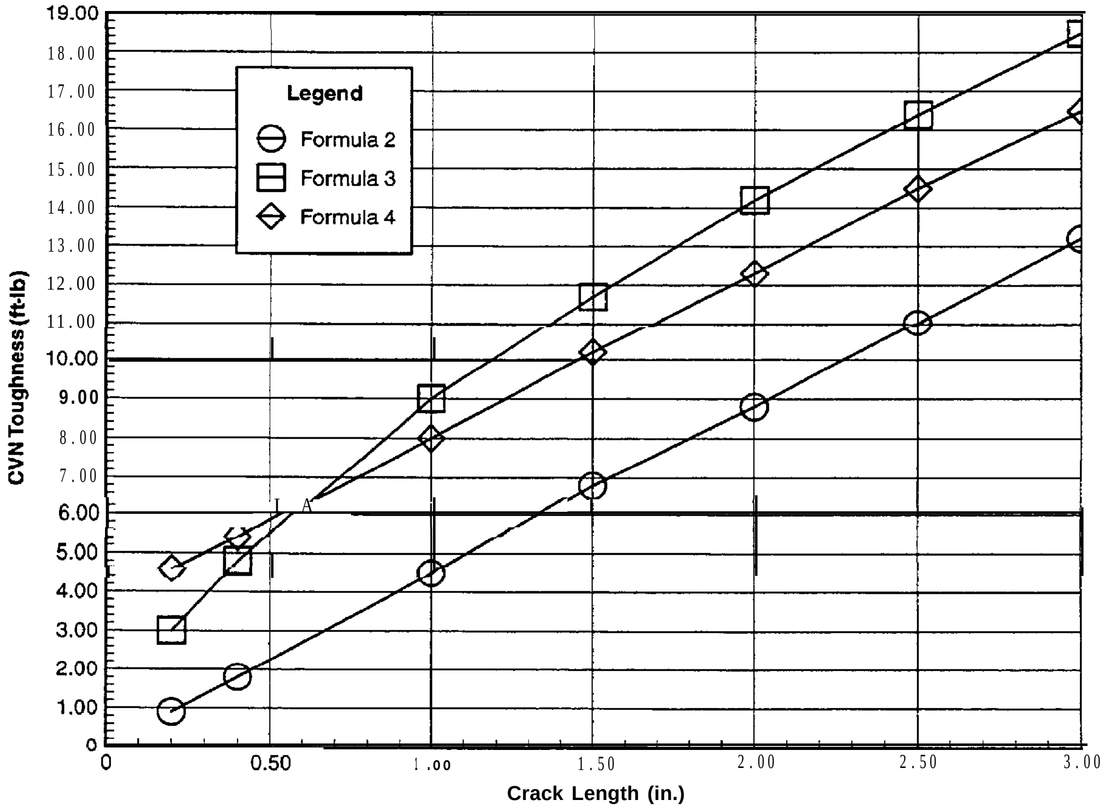

Figure 1—CVN Values for 75K Material-Surface Crack and 50 ksi Stress

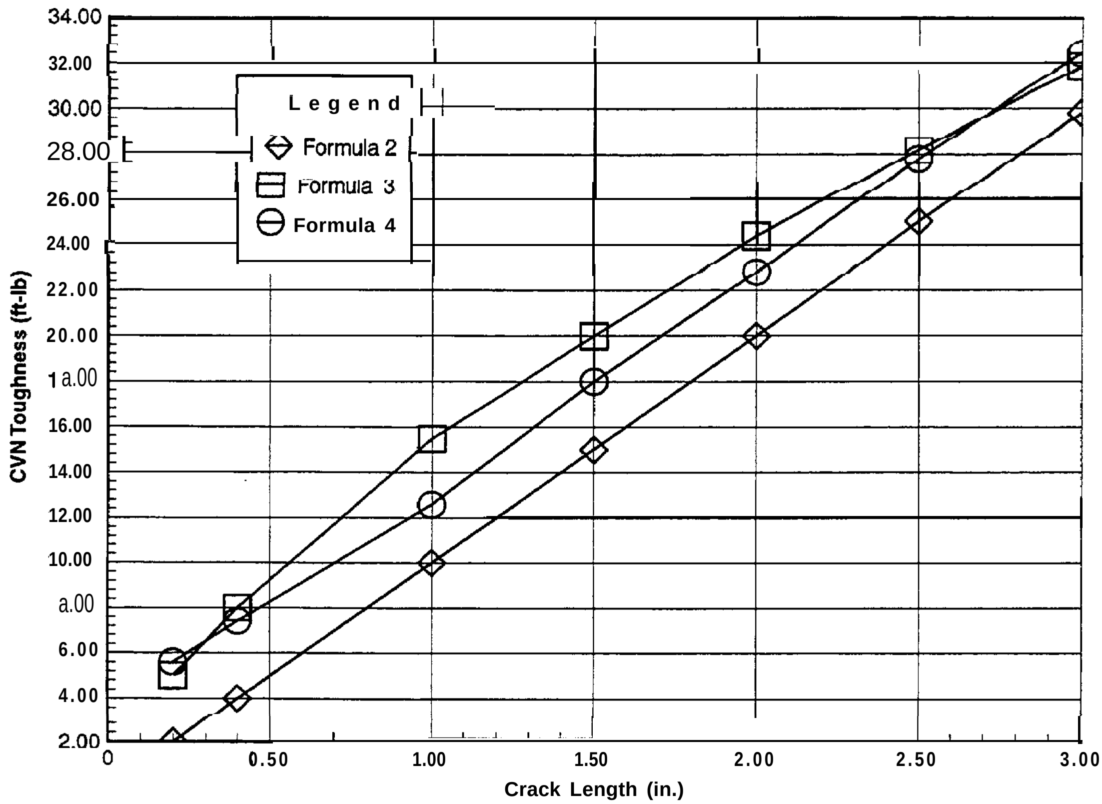

Figure 2-CVN Values for 75K Material-Surface Crack and 75 ksi Stress

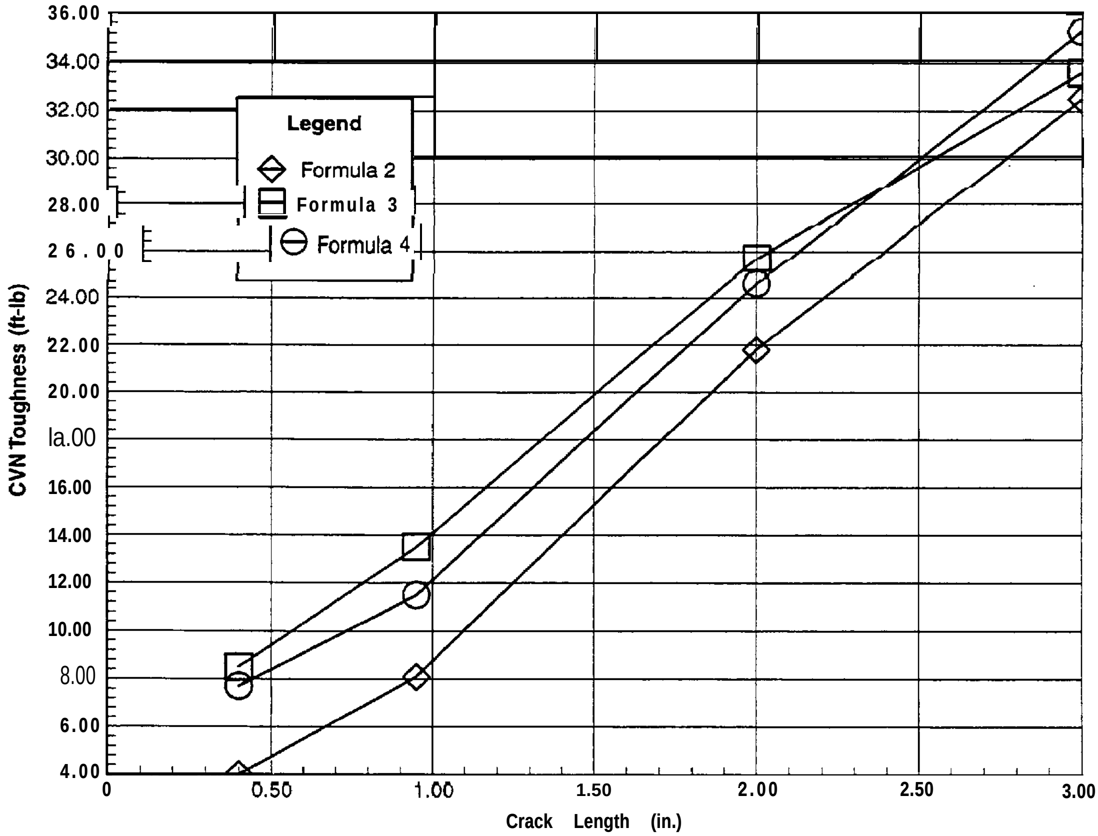

Figure 3—CVN Values for 75K Material-Volumetric Crack and 50 ksi Stress

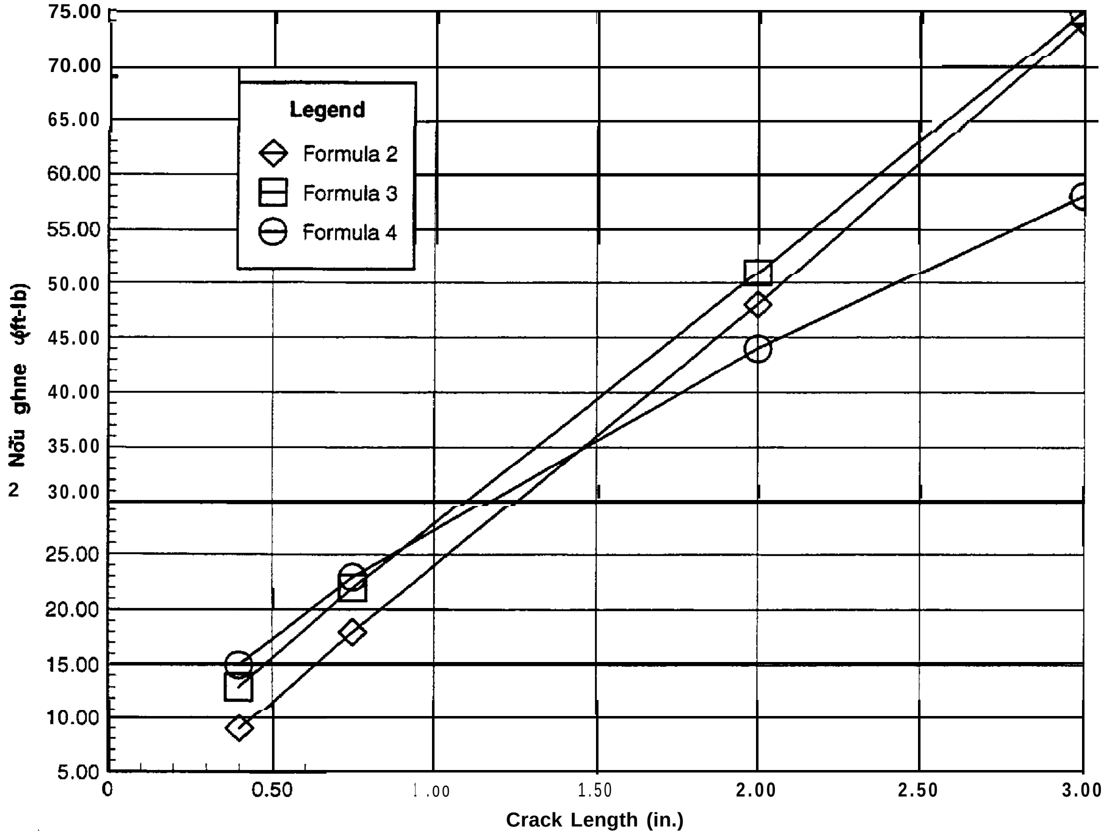

Figure 4—CVN Values for 75K Material-Volumetric Crack and 75 ksi Stress

APPENDIX A-REFERENCES AND BIBILIOGRAPHY

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