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Significance of Fracture Extension Resistance (R-curve) Factors in Fracture-Safe Design for Nonfrangible Metals

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ABSTRACT

Requirements for new directions in fracture research emerge from considerations of the basic lack of applicability of K parameters for definition of the fracture extension resistance of nonfrangible metals. New research is required into factors relating to the increase in plastic work energy resistance defined by R curves. The urgency of such studies evolves from the increasing use of metals of low-intensity plane stress (low-shelf, low-tearing-energy) characteristics in structures of high-compliance features. A case is presented for the mutual consideration of metal-type structure-type relationships in fracture-safe design. Present fracture-safe design practices do not include a rational approach to this question.

The report provides an introduction to these considerations in terms of extension of fracture mechanics concepts, as well as metallurgical factors and engineering practices. The importance for understanding the interaction of these factors cannot be overstated, and considerable emphasis is placed on introductory aspects. Data presentation of R-curve research is limited to illustrative examples, which document the reality of fracture extension processes in determining conditions for structural failure. The report is intended as a precursor to topical reports on the subject.

A rationale is presented for the use of the Dynamic Tear (DT) test in standard and modified configurations, which provide for definition of R-curve features. Indexing of the R-curve features to the Ratio Analysis Diagram (RAD) adds new dimensions to analytical capabilities of this system. The integration of mechanical, metallurgical, and structural aspects which emerge should provide for significant advances in treating the fracture-safe design problems of nonfrangible metals and compliant structures.

PROBLEM STATUS

This is the first in a series of reports concerned with the topic of defining parameters applicable to the fracture-safe design of nonfrangible metals.

AUTHORIZATION

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LIST OF SYMBOLS

R	resistance to fracture extension
$\mathcal{G}$	strain energy release rate with crack extension
$\mathcal{G}_c$, $\mathcal{G}_{Ic}$	critical values of $\mathcal{G}$ for elastic fracture; $\mathcal{G}_{Ic}$ refers to the plane strain state, while $\mathcal{G}_c$ refers to the plane stress state
K	stress intensity factor
K_c	critical value of K for unstable crack extension under the plane stress state
K_{Ic}	critical value of K for plane strain crack extension at slow loading rates
K_{Id}	critical value of K for plane strain crack extension at dynamic loading rates
K_x	questionable or invalid values of K due to excessive plastic deformation of the crack tip
a	depth of surface or edge crack
Δa	fracture extension increment
a_o	original crack dimension
r_n	radius of crack tip
COD	Crack Opening Displacement measured at the surface of a cracked plate
σ	applied stress
σ_f	failure stress
σ_{ys}	yield strength of material
ϵ_c	critical strain for crack extension
B	thickness dimension of specimen or plate
C_v	standard Charpy-V notch test
DT	Dynamic Tear Test
E/A	energy per fracture area measured in DT test
R_p	constant which defines resistance to plastic fracture in terms of DT energy
RAD	Ratio Analysis Diagram
Ratio	refers to lines of constant K_{Ic}/σ_{ys} on RAD
FAD	Fracture Analysis Diagram

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SIGNIFICANCE OF FRACTURE EXTENSION RESISTANCE (R-CURVE) FACTORS IN FRACTURE-SAFE DESIGN FOR NONFRANGIBLE METALS

INTRODUCTION

One of the most basic requirements in fracture research is that the test specimens must model the behavior of structures which contain flaws. A second requirement is that the test specimens must provide fracture resistance measurement capabilities which are appropriate for the ductility level of the metal. In analyzing the significance of fracture test data, it must be recognized that the behavior of structures derives both from the type of mechanical force system and the type of metal. The mechanical aspects involve the relative compliance characteristics which determine the stored energy available for fracture propagation. The metallurgical aspects involve the relative ductility characteristics which determine the energy absorption capacity (resistance) to fracture initiation and extension. These two factors act in concert to determine how the structure will respond to loading in the presence of flaws. The essence of fracture-safe design is the assessment of these interactions.

There are broad varieties of metal-type structure-type combinations for which the bases of fracture-safe design lie squarely in the conditions for fracture *initiation*. Accordingly, the specimen modeling must relate to conditions for initiation of fracture. There are equally broad varieties of metal-type structure-type combinations for which the bases of fracture-safe design must be found in the conditions for *extension* of the fracture. For these cases, the specimen modeling must relate to the extension aspects.

The fracture research activity of the past twenty years has been dedicated almost totally to questions of fracture initiation for relatively brittle metals; as a result, satisfying solutions are now available. Since the problems of fracture extension have been largely neglected, very few principles exist for engineering guidance. It is timely that attention be given to these unresolved problems because they are rapidly becoming of major engineering consequence. It is also timely to inform the engineering community of the issues involved, so that the new research activities will be understood in principle.

METAL-TYPE STRUCTURE-TYPE RELATIONSHIPS

A large and growing fraction of the structural metals in engineering use may feature low or intermediate levels of resistance to the propagation of plane stress (nonbrittle) fracture. These features may also be described as "low shelf" or "low tearing energy"—both terms have the same meaning. Such characteristics are inherently related to the metallurgical factors which control microfracture processes*. The low-shelf metals cannot be influenced significantly by temperature or by modifications of strength within the range of the class.

Since the low-shelf metals are neither brittle nor highly ductile, the engineer is confronted by an "in-between" state of semiductile fracture. The basic question for the

*See Appendix A for a discussion of the metallurgical factors.

semiductile state is that of fracture extension by low-energy tearing. Whether or not fracture will result by the extension of a low-energy tear requires reasonably refined consideration of the type of structure and levels of stress imposed. There are two basic types of structures—rigid and compliant. Rigid structures have limited capability for release of elastic strain energy, generally sufficient only for fracture extension involving relatively brittle metals. Compliant structures may feature high total energy, sufficient to cause fracture extension for relatively ductile metals.

Aluminum and titanium alloys are generally characterized by low to intermediate levels of resistance to tear extension, except for the lowest strength levels. The low-strength steels generally feature high levels of tear resistance, except for conditions of excessively preferential alignment of inclusions (e.g., weak directions of rolled or forged products). The intermediate-strength steels present a special case of major engineering proportions, deserving detailed explanation.

The immediate importance of the intermediate-strength steel case evolves from prior experience with low-strength steels. This experience has led to the incorrect assumption that restricting service temperatures to above the cleavage-to-ductile fracture transition provides positive assurance of fracture-safe performance. Unfortunately, this is not always the case for these steels, and structural failures have been experienced involving fractures which "do not show cleavage." Thus, the unexpected structural failures have been the cause of alarm and confusion. Actually, such failures should be expected, if the basic factors involved are understood in terms of metal-type structure-type relationships.

The new problems result from four interrelated factors:

1. Increasing interest by designers in the use of intermediate-strength steels of 70 to 130 ksi yield strength (50 to 90 kg/mm^2).

2. Economic competition to supply these steels with minimum cost increase over that of the conventional low-strength steels. This requirement tends to promote the use of production practices which result in low-shelf (low-tearing-energy) type steels.

3. Relatively high stresses which are applied to these steels. This factor results in very high stress intensities at flaw tips, which induce crack initiation.

4. Extensive utilization of these steels in structures of high-load-compliance features. As the result, the mechanical force for continued tear extension may increase rapidly with enlargement of the tear.

These factors describe directions in the evolution of low-cost, intermediate-strength steels, which tend to be opposite to the requirements of the type of structures that have generated the interest in the higher strength levels. These same opposing directions tend to carry over in the heat-affected-zone (HAZ) and weld characteristics.

There is no intent to present a case that only high-shelf materials should be used. The important point is that fracture research should be directed to the characterization of fracture extension factors. In general, the problem requires engineering definition of the lowest level of tearing energy that should be used for particular applications. Test methods are required which provide a significant measure of the resistance to tear extension.

The nomenclature of tear extension, as contrasted to crack extension, requires explanation because the terms are often used interchangeably. A mechanically correct definition should recognize crack extension as fracture with retention of the sharp features of the crack tip. Fracture extension involving appreciable blunting of the crack tip is best described as tear extension. Thus, brittle fractures are of crack extension type and the semiductile or ductile fractures are of tear extension type. A dividing line is best placed in the transition between plane strain and plane stress fracture characteristics.

The nomenclatures of plane strain and plane stress also require clarification because of the qualifications which are used in the different literature sources. In the context of mathematical usage, plane strain is defined as a condition of zero plastic flow parallel to the crack front. Plane stress is defined as a condition of zero stress in the same direction. The mathematical definitions represent extreme conceptual limits, ranging from total constraint to plastic flow to zero constraint.

For real metals, the constraint level cannot extend to either of these two extremes, i.e., it can neither be total nor zero. Brittle metals develop very little plastic flow and, therefore, fracture under conditions close to idealized plane strain constraint. Highly ductile metals develop large amounts of plastic flow and, therefore, fracture under conditions which approximate the idealized plane stress constraint. With the advent of linear-elastic fracture mechanics (LEFM), the definitions were restricted to constraint conditions which could be measured by K-type tests. Fracture ductility in excess of K_{Ic} or K_{Id} levels (plane strain) was defined as K_c, meaning plane stress. It should be noted the K_{Ic}, K_{Id}, or K_c parameters are limited to initiation and propagation of fracture under purely elastic loading. In the context of the discussions of this paper, the K_c level of plane stress for metals of plate thickness is considered to be a very small increment (first signs) of fracture ductility above that of the plane strain level. The very large increments in ductility above this level which are characteristic of highly ductile metals are properly recognized as plane stress in keeping with the mathematical definitions.

THE R-CURVE EXPRESSION OF FRACTURE EXTENSION RESISTANCE

Fracture mechanics research in the early 1960's was directed to measurement of the fracture extension resistance of metals in terms of the plastic work energy parameter $\mathcal{G}_c$ *. The fact that the expression is valid only for conditions of nominal elastic loads, and for other reasons involving experimental complexities, led to an early end of this effort. The feature of "rising $\mathcal{G}$" in the fracture extension of metals was defined as the resistance curve (R curve). The prior fracture research of the 1950's recognized that the resistance to fracture increased with extension from a crack tip for the case of ductile metals. However, the metals of interest at the time were low-strength steels of high-shelf (high-ductility) type, and quantitative investigations were not deemed necessary.

Fracture extension resistance characteristics are best considered in terms of the separation of metals into two broad classes—frangible (unstable extension) and nonfrangible (stable extension). The frangible category applies not only to metals, but also to all brittle solids. The generic aspect of this grouping is that fracture extension occurs by release of elastic strain energy. That is to say, the first unit extension of the fracture from a crack tip releases sufficient elastic energy to fracture the next element. The fracturing process thereby is self-sustaining (unstable) in propagation through elastic, tensile stress fields.

The generic aspect of the nonfrangible category is that fracture extension cannot occur by release of elastic strain energy. In this case the plastic zones are relatively large and absorb plastic work energy in excess of that which can be provided by the elastic strain field. As a consequence, the process of fracture extension requires continuous reapplication of plastic loads (stable extension) to the tear tip region to cause a succession of rupture increments.

*See Appendix B discussion of the fracture mechanics aspects of R-curves.

A most important additional aspect for nonfrangible metals is that the fracture extension resistance increases (to a limiting characteristic value) with movement away from the initial crack tip. For frangible metals, the fracture extension resistance remains at the same level, or actually decreases (for rate-sensitive steels). Thus, the frangible metals feature a "flat" nonrising R curve. The nonfrangible metals feature rising R curves, ranging from a shallow to a very steep rise, depending on the intrinsic metallurgical ductility.

The physical significance of the rate of rise of the R curve with fracture extension should be understood in a generalized sense before entering into more detailed discussions. Figure 1 presents schematic illustrations for purposes of such introduction. The figure illustrates a metal section containing a sharp elliptical surface crack, subjected to tensile loading. The increments of crack (or tear) extension are defined as Δa, and a_o is the initial crack depth.

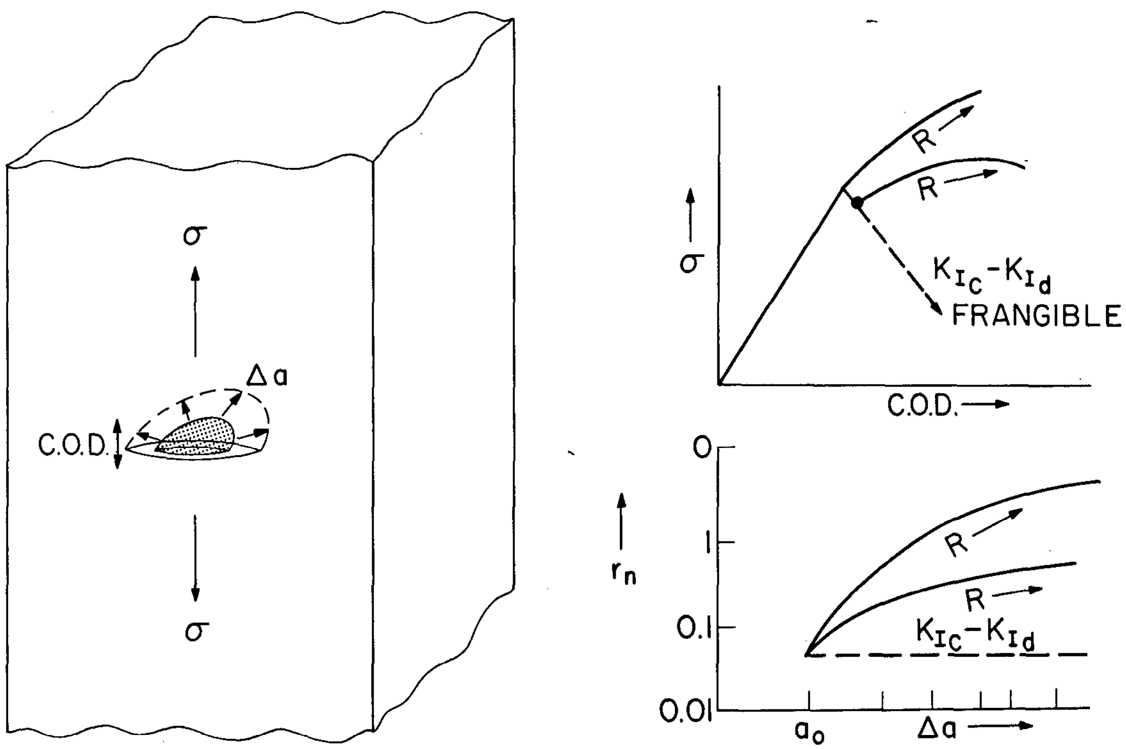

Fig. 1 - Physical significance of increased resistance R to fracture extension for ductile metals (solid curves), as compared to frangible metals (dashed curves). Note that K_{Ic}-K_{Id} parameters apply only for the frangible metals which do not feature increased R. The physical aspects relate to the load stress σ and the crack tip blunting r_n.

The top graph of Fig. 1 illustrates the σ -COD traces that may be expected for frangible metals and for metals featuring rising R curves. In principle, the crack opening displacement (COD) can be related to the Δa extension by calibration. COD may be measured by the use of a clip gage. For ductile metals, COD (and Δa) occurs with rising load into the plastic region (rising R) without evidence of unstable fracture extension. For a frangible metal, the COD gage detects an "instability" at elastic stress levels, followed by unstable fracture.

The effects on the crack tip geometry are illustrated at the bottom of the figure by the r_n-Δa plot, where r_n signifies the crack tip radius. The important aspect is that very large differences in crack blunting result from the extension of fractures for metals of different R-curve features as follows:

Nonrising R curve—Crack tip sharpness is retained because the critical plastic zone size is small.

Shallow-rising R curve—Crack tip blunting occurs gradually by a process of increasing plastic zone size. The small degree of blunting, developed in the first unit extension, results in forming a larger plastic zone size for the next step, which causes additional blunting and, therefore, an additional growth of the plastic zone size, etc. A stable condition is achieved, following which there is no further increase in r_n.

Steeply rising R curve—Crack tip blunting occurs rapidly as the result of gross plasticizing of the zone in advance of the tip, starting with the first rupture increment. The effects are then accentuated in further extension; again there is a leveling-out to a stable r_n configuration.

Increases in plastic work energy per unit extension (E/A) will evolve due to the crack blunting and plastic zone size increases. The magnitude of the E/A increases in the course of fracture extension for ductile metals is related to the rate of rise of the R curves.

The rate of rise of the R curves will be reflected in the nominal engineering stress required for fracture extension as follows:

Nonrising R curve—Unstable fast fracture occurs at the level of nominal elastic stress required for initiation.

Shallow-rising R curve—The nominal stress required for stable tear extension increases gradually with extension. While the first extension may be at elastic stress levels, continued extension may require over-yield stress conditions.

Steeply rising R curve—The nominal stress required for the initial tear extension will exceed yield and then require an increase of the plastic load stress for continued extension.

It is important to recognize that most of the fracture research activity of the past decade has involved studies of K_{Ic} or K_{Id} parameters for frangible metals which feature nonrising R curves. It is well understood that valid K_{Ic}, K_{Id}, or K_c parameters cannot be measured for metals which feature steeply rising R curves. The practice of quoting K_x (invalid) parameters for such ductile metals is without scientific basis and has no analytical potential. The claim that the K_x values represent "lower bound" estimates, and therefore are "conservative," results in confusion because the values are then used for unrealistic flaw size-stress level calculations of fracture initiation conditions.

There are no fracture mechanics tests which can define R-curve factors that involve plastic stresses. In fact, there is no basic theory which would provide for analytical procedures or guidance in evolving such tests. Certainly, for the next decade at least, solutions to pending problems of low-shelf metals must be found in correlations of prototype structural tests with practical laboratory tests that measure fracture extension resistance in terms of R-curve slopes. Since fracture extension resistance is a matter of energy absorption, tests of an energy measurement type are ideally suited for the purpose.

A practical procedure for the definition of R-curve characteristics has been evolved by adjustment in the configuration of the Dynamic Tear (DT) test specimen, as will be described in the following section.

CONCEPT OF DT TEST CONFIGURATION ADJUSTMENT PROCEDURE FOR DEFINITION OF R-CURVE CHARACTERISTICS

The basic aim which determined the configuration of the standard DT test (1) is the measurement of fracture extension energy. The general geometry of the test is similar to that of the fracture mechanics edge-notch-bend test. The thickness B of the test establishes the maximum attainable mechanical constraint for both methods. The sharp crack, or sharp tip notch, must be of sufficient depth so that the full mechanical constraint of the section size is attained. This feature is common for both tests. Excellent correlations of DT fracture energies and K_{Ic} values have been documented (2) for metals which feature a nonrising R curve. Such correlations should be expected because of the common geometric features. The first event (initiation) of crack extension is *the* significant aspect for measurement of valid K_{Ic}-K_{Id} characteristics. While the DT fracture extension energy is low for such metals, it increases with an increase in the K_{Ic}/σ_{ys} ratio because the related plastic zone size increase is common for both tests. In effect, the DT test is an inexpensive method for indexing the K_{Ic}/σ_{ys} ratio for frangible metals. The correlations with fracture mechanics tests involving increased thickness dimensions B provide for indexing to K_{Ic}/σ_{ys} ratios in excess of those which relate to DT specimens of small thickness dimensions.

The foregoing discussions described the use of the DT test in measurements of plane strain fracture toughness. The relatively long fracture extension path of the DT test also provides for measurement of plane stress fracture toughness. This feature may be understood in terms of the effects of test specimen configurations. Figure 2 presents schematic drawings for three types of fracture test configurations. The top schematic drawing labeled 1 illustrates a *fracture-mechanics test* which is configured and instrumented to detect the conditions for the initial extension of a crack. Frangible metal is thus characterized by the K_{Ic} or K_{Id} parameters. A ductile metal of steeply rising R-curve features would be "characterized" by a K_x (invalid) measurement.

The schematic drawing labeled 3 at the bottom of the figure represents the standard DT test geometry noted as a *plane stress configuration.* The feature of this configuration is that sufficient fracture extension path is provided to *allow* the development of whatever degree of plane stress fracture toughness that is characteristic of the metal. The drawing indicates the fracture extension transition from a small plastic zone at the crack tip (plane strain) to a large plastic enclave (plane stress), which is characteristic of a ductile metal.

The schematic drawing labeled 2 at the center of the figure illustrates a "reduced-run" version of the DT test. It is defined as a *plane strain configuration* because the growth of the plastic enclave is largely prevented due to inadequate fracture extension path. There is no intent to claim that the conditions are fully equivalent to the plane strain constraint acting at the crack tip. The intent is to obtain an energy absorption measurement, by practical procedures, which is related to a condition which approaches plane strain constraint.

The graph at the top of Fig. 2 illustrates schematically the rise of the energy per unit fracture area (E/A) measured by the three test methods. The E/A value for the fracture mechanics test (expressed by $\mathcal{G}$, which is an E/A measurement) relates to the full-constraint condition acting at the crack tip. The E/A value for the plane strain DT configuration should show an increase which is related to a decrease in the level of plane strain constraint. The E/A value for the plane stress DT configuration should show an

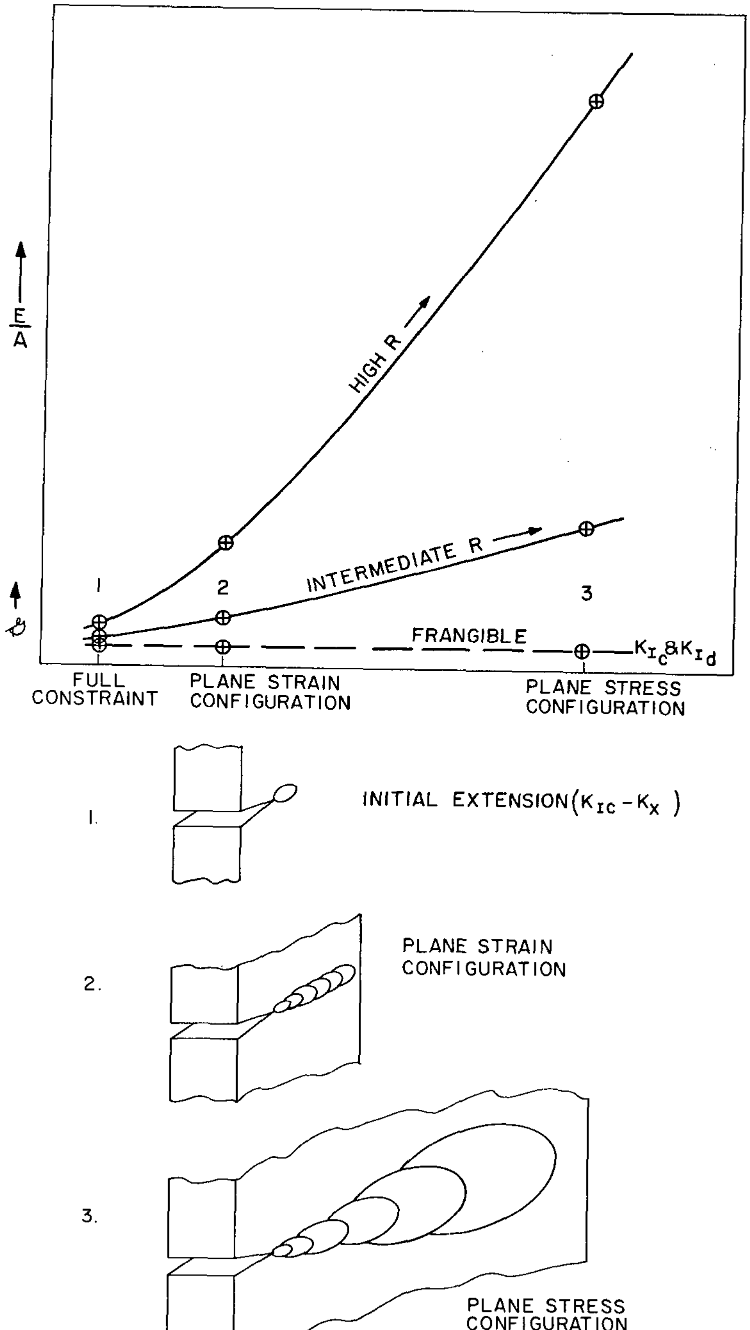

Fig. 2 - Definition of R-curve features by various tests, including (1) fracture mechanics tests which only measure features of initial extension, (2) the plane strain DT configuration test, and (3) the standard DT test which represents a plane stress configuration. The solid curves indicate increasing R, typical of a ductile metal.

additional increase, which is related to loss of constraint as the plane stress state evolves. The three curves of the figure represent metals of frangible (flat curve), shallow-rise and steep-rise R-curve characteristics. The slopes indicate the Δ a rate of transition to lower levels of constraint, i.e., rate of transition to plastic fracture. A practical procedure for measurement of the R-curve slopes evolves from comparison of the E/A values of the two DT test configurations labeled 2 and 3 in Fig. 2.

It is interesting to note that the Charpy-V (C_v) test configuration results in a mechanical constraint condition of near-plane strain type (3). Figure 3 illustrates the change in fracture appearance resulting from the increase in the fracture path length of the C_v test specimen. An appreciable increase in the E/A value results from the change in configuration for metals of high-shelf features. It should be noted that C_v test specimens never show full slant fracture, even for the most ductile metals. In effect, the C_v test configuration provides a measurement of fracture extension resistance differences that are related to point 2 of the curves presented in Fig. 2. The larger differences that are measured at point 3 are not disclosed. In simple terms, the C_v is not configured appropriately for characterization of plane stress fracture extension resistance properties. Additional complications result from the dull notch of shallow depth which causes gross deformation to occur in the crack initiation phase because of inadequate mechanical constraint. Both factors act to becloud the significance of the energy measurement and are the basic reason for the complexities in the interpretation of C_v test values, if a broad range of metals are to be compared.

Similar changes in fracture appearance of the DT test in the two configurations are indicated by Fig. 4. The illustration relates to a steel of high-shelf, steeply rising,

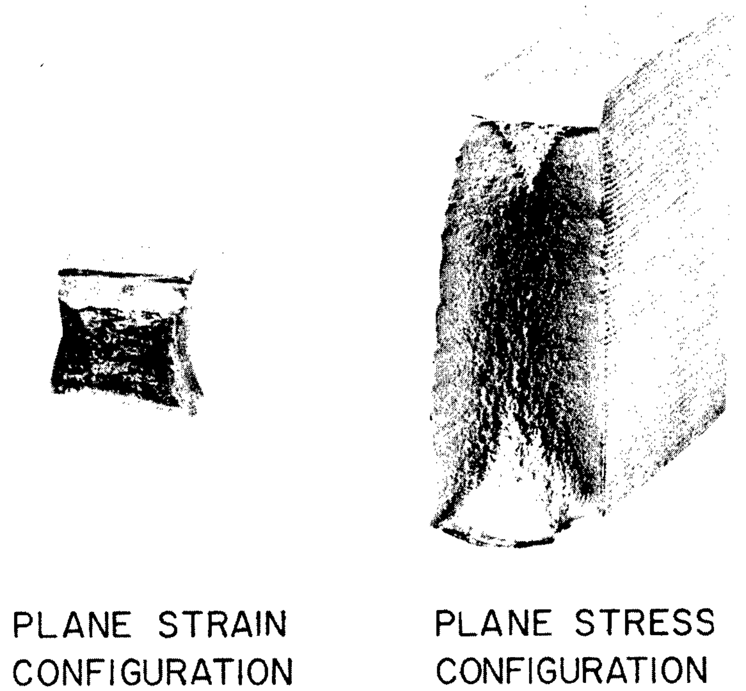

Fig. 3 - The geometry of the standard Charpy-V (C_v) test is of the plane strain configuration type. Increasing the fracture extension distance for the C_v test results in a fracture transition from essentially flat to slant fracture features (plane strain to plane stress). The standard C_v test never develops a slant fracture, even for highly ductile metals, because of the configuration features.

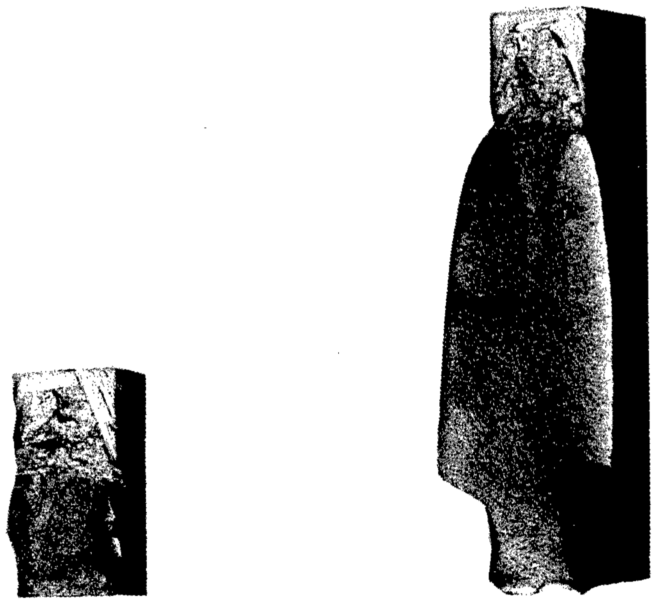

Fig. 4 - This illustration shows the change in fracture appearance features of the DT test for the plane strain and plane stress (standard) configurations. The fractures are representative of the plane strain to plane stress transition for a ductile high-shelf steel. The difference in energy per unit fracture area (E/A) values for the two test configurations defines the slope of the R curve.

R-curve characteristics. This is evident by the development of a full-slant fracture for the standard DT test configuration. The gross deformation of the notch displayed by the C_v test is eliminated by the higher constraint of the deep DT test notch.

DT TEST INVESTIGATION OF R-CURVE CHARACTERISTICS

We shall now present experimental data which involve the use of the DT test in a wide variety of configurations, as well as "low blow," limited-energy-delivery techniques. These experiments vividly illustrate the R-curve aspects of a wide variety of steels. Documentation of the basic significance of the two-configuration DT test approach emerges from this broad range of studies. Moreover, the meaning of DT energy values in the plane stress portion of the Ratio Analysis Diagram (RAD) becomes clear (2,4).

In order to study the R-curve features of these structural steels, the DT test specimen configuration was modified by introducing variations of fracture length for a given thickness. Figure 5 illustrates the details of the test specimen design. The steels selected for R-curve studies were 1-in.-thick plates, representing a wide range of yield strength and DT test shelf properties. Tables 1 and 2 present the chemical compositions and mechanical properties of these steels, respectively. The tests were conducted at temperatures corresponding to the upper shelf, i.e., above the temperature transition region.

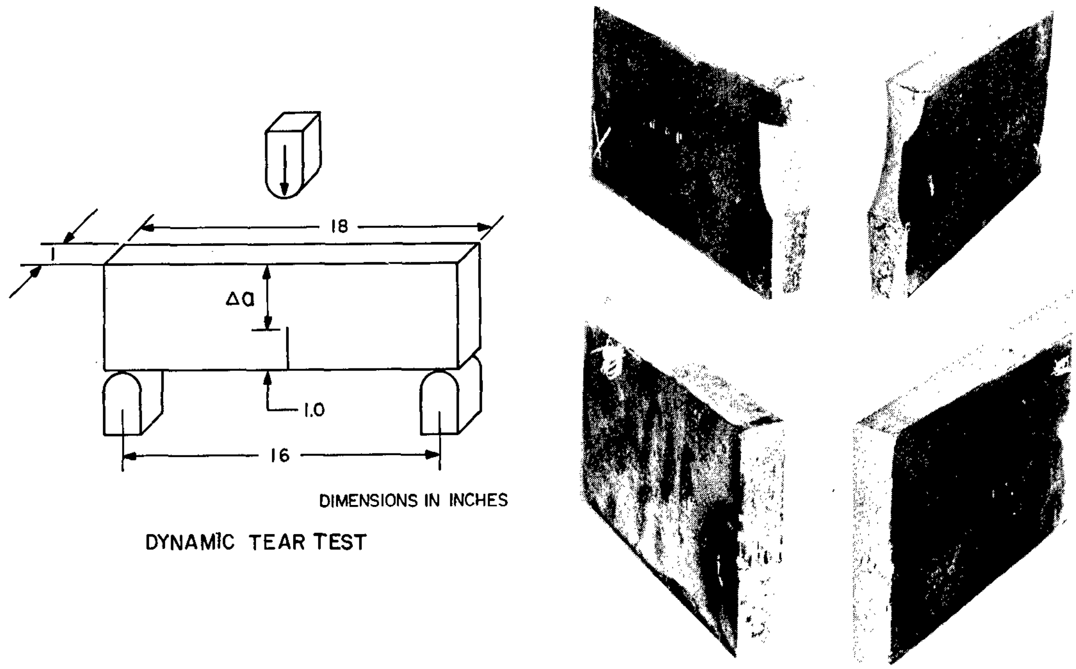

Fig. 5 - Fractures of the standard 1-in. DT test specimen which are representative of a ductile high-shelf steel (top) and a frangible steel (bottom). In these studies the fracture extension length was varied (Δ a) in order to define R-curve features. The same depth of brittle weld was used in all cases to enforce the highest degree of plastic constraint provided by the section size (1.0 in.) The brittle weld bead may be replaced by a slit (of the same depth) with a sharpened tip, obtained by a pressed knife edge. This procedure does not affect the measured E/A values, which depend on the energy absorbed in extension of the fracture.

A graphical representation of the range of properties is shown by plotting these data on the steel RAD, Fig. 6. Seven of the steels of this study involve plane stress fracture properties, as shown by the location of the data points above the 0.63 ratio line. This line is the upper limit of plane strain fracture toughness for 1-in.-thick plates. The reference code for these seven test steels indicates the relative position of the steel in the RAD, i.e., low (L), medium (M), and high (H). Steel F-1 lies below the 0.63 ratio line and, therefore, should be characterized by the plane strain fracture toughness (K_{Ic}) scale.

The method of RAD plotting should be explained at this point. The section thickness B determines the maximum plane strain constraint that can be developed at the tip of a through-thickness crack (or plate-edge crack). The edge crack of fracture mechanics test specimens and of the DT test "models" a through-thickness crack. With increasing K_{Ic}/σ_{ys} ratio value, there is an increase in plastic zone size, i.e., increasing ratio signifies increasing metal ductility. Since a given section thickness provides a fixed value of mechanical constraint, there is a limit to the plane strain K_{Ic}/σ_{ys} ratio value that can be measured—for a 1 in. thickness this limit is 0.63. As the intrinsic metal ductility begins to exceed this ratio value, the mechanical constraint becomes inadequate for measurement of valid plane strain fracture toughness. With an additional increase in metal ductility, unstable brittle fracture cannot develop in such a plate, and some degree of through-thickness yielding (contraction) will evolve, i.e., plane stress.

Table 1
Chemical Compositions of Steels Used in R-Curve Studies

Steel Code	Primary Alloy Elements (%)									Other Elements (%)
	C	Mn	Si	P	S	Ni	Cr	Mo	V	
F-1	0.39	0.65	0.350	0.005	0.008	1.69	0.88	0.21	--	0.03 Al
L-1	0.20	0.43	0.21	0.006	0.007	3.28	1.66	0.75	--	
L-2	0.18	0.58	0.28	0.015	0.019	0.05	0.69	0.19	0.03	0.10 Al
L-3	0.20	0.10	0.005	0.006	0.003	8.9	0.91	0.92	--	4.5 Co
M-4	0.18	0.89	0.24	0.010	0.023	tr	0.52	0.17	0.03	0.03 Cu, 0.03 Ti
M-5	0.20	0.43	0.21	0.006	0.007	3.28	1.66	0.75	--	--
H-6	0.19	0.32	0.20	0.007	0.004	3.20	1.62	0.72	--	--
H-7	0.12	0.32	0.17	0.006	0.014	2.33	1.26	0.34	--	--

Table 2
Mechanical Properties of Steels Used in
R-Curve Studies

Steel Code	YS		UTS		RA	E1	Shelf Level DTE	
	(ksi)	(kg/mm²)	(ksi)	(kg/mm²)	(%)	(%)	(ft-lb)	(kg-m)
F-1	120	84	149	105	30	12	300	42
L-1	162	114	185	130	48	14	1450	200
L-2	111	78	117	82	53	16	2100	290
L-3	183	128	201	141	66	18	2900	400
M-4	98	69	108	76	43	17	2720	376
M-5	125	88	141	99	61	19	4390	607
H-6	144	101	159	112	61	18	6650	920
H-7	83	58	98	69	68	24	6570	910

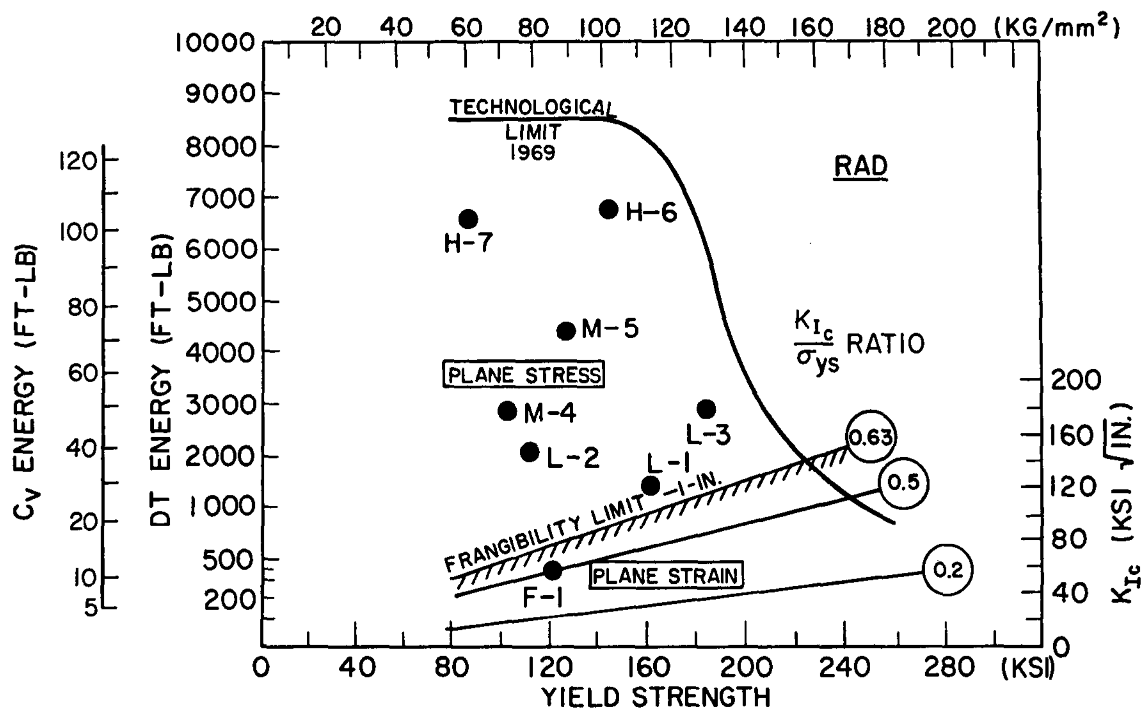

Fig. 6 - Location of the test steels in the plane strain and plane stress regions of the Ratio Analysis Diagram (RAD). For steels with a thickness B of 1-in., plane strain fracture is limited to the zone below the 0.63 ratio line. The RAD prediction is based on the fracture mechanics relationships $B = 2.5\,(K_{Ic}/\sigma_{ys})^2$ for plane strain fracture (see Table 3).

The ratio lines of the RAD define the section size that is required to develop plane strain. The absence of ratio lines above 0.63 in Fig. 6 indicates that the higher ratio values, depicted in the conventional RAD, have no meaning for plates of 1 in. thickness—hence, these are not shown. The significance of DT energy values, which lie above the 0.63 ratio line, is that they represent increasing resistance to plastic (plane stress) fracture.

The RAD location of steel F-1 signifies that plane strain fracture toughness K_{Ic} is the appropriate characterization parameter, and that unstable fracture extension should result, following the "first event" of initial extension at the crack tip. The R curve for this steel should be "flat" (nonrising). The test data confirmed these expectations—the E/A values for specimens of short- and long-run geometrical features remained constant at a low value, 100 ft-lb/in.^{2}, Fig. 7. The fracture appearance was flat, without evidence of shear lips, for all test configurations.

The high-shelf RAD location of steel H-6 signifies a high level of plane stress fracture resistance. The R curve for this steel should be expected to exhibit a steep slope, deriving from gross blunting of the crack tip and the formation of a large plastic enclave. The expected large increase in E/A with tear extension length is illustrated in Fig. 8. The changes in fracture appearance with increases in fracture extension result from the changes in DT configuration from the plane strain to the plane stress type. The series thus serves to "model" the natural processes of transition (decreasing mechanical constraint) from plane strain to plane stress with tear extension. Each specimen provides an average E/A value for the limit of the allowed extension. That is to say, the R curve is defined by integrated average values of E/A. The aspects of crack tip blunting and formation of the plastic enclave will be described in relation to the low-blow tests.

The low-shelf RAD location of steel L-1 signifies low plane stress fracture resistance. The R curve should be expected to exhibit a low slope, deriving from the slight blunting of the crack tip and the formation of a small plastic enclave. The expected behavior of this steel is confirmed by the data presented in Fig. 9. The shallow R curve is indicative of a much slower buildup of E/A with increasing Δa as compared to the high-shelf steel H-6 described above. The fracture surfaces pictured above the curve demonstrate that this steel does not attain conditions of full-slant fracture, as should be expected from the limited rise of the R curve. The characteristic metallurgical ductility of this steel is not sufficient to cause crack tip blunting, as will be illustrated. Thus, the fracture extension resistance is only marginally above that of frangible materials. These various features are predictable from the RAD location, barely above the 0.63 ratio line for plane strain.

The physical aspects of relative degrees of crack tip blunting and plastic enclave development may be examined by incremental loading of the standard DT specimen (Δa = 3 in.). The input energy was increased in steps to the level required for complete fracture of the H-6 and L-1 steels. The "low-blow" technique tests were conducted using a drop-weight machine. The results of these tests are summarized in Fig. 10. The physical aspects of the fracture extension process are illustrated by the photographs in Fig. 11 and are described as follows:

High-shelf H-6 steel—The first blow of 1000 ft-lb energy cracked the brittle crack starter weld and formed a small dimple at the tip of the flaw. A second blow of 1000 ft-lb on the same specimen did not produce any visible crack growth on the surface of the specimen; the dimple at the crack tip enlarged to approximately 1/4-in.-diameter after the second blow. Using a new specimen, an input energy value of 1500 ft-lb cracked the weld and formed a 1/2-in.-diam dimple at the crack tip, but no propagation of the crack into plate material could be observed at the plate surface. The second blow of 1500 ft-lb resulted in a ductile tear extension to approximately 1/2 in. Three succeeding tests (utilizing separate specimens) at 2000, 3000, and 4000 ft-lb resulted in tear extensions

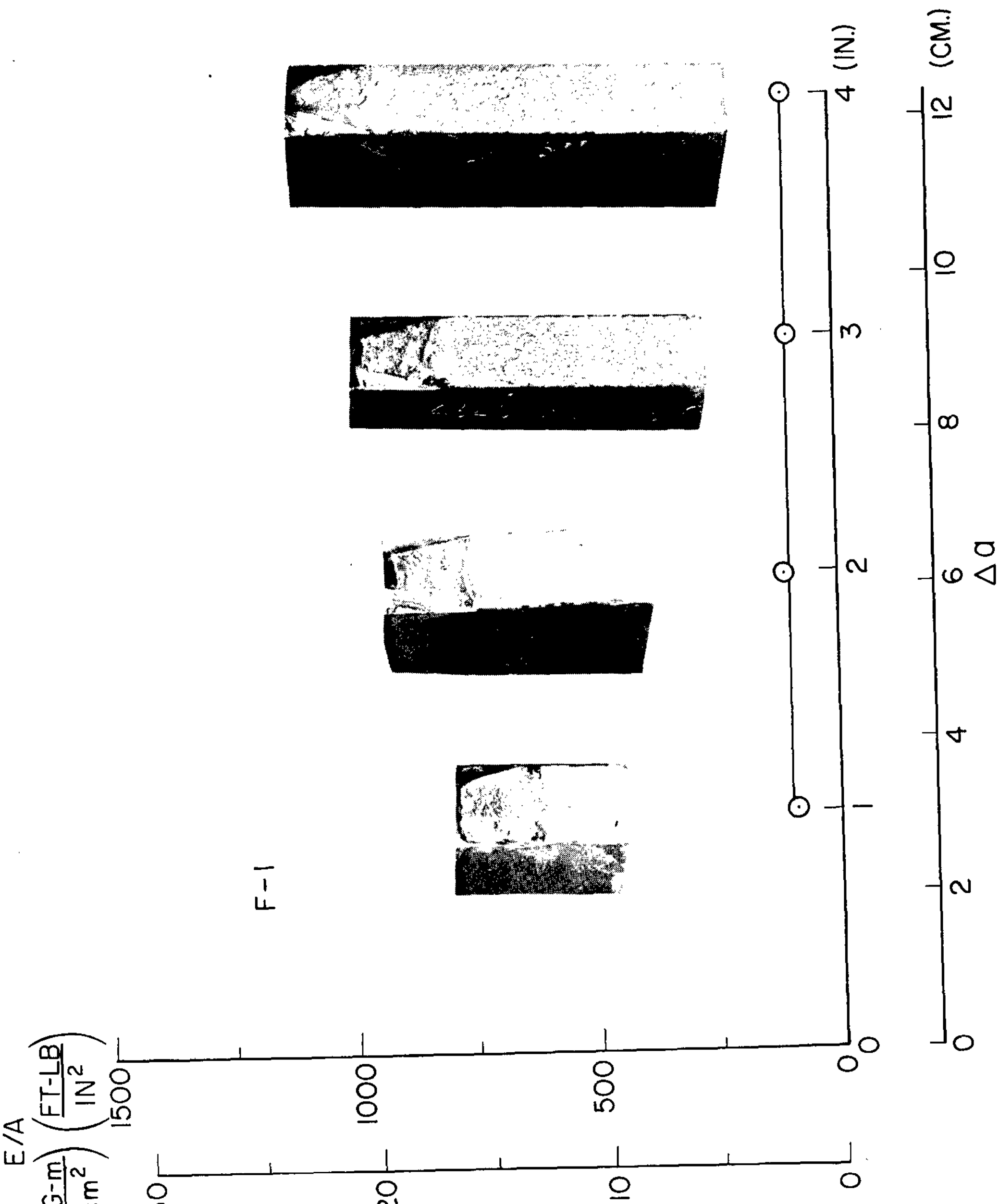

Fig. 7 - Fracture appearance and R-curve features for the frangible F-1 steel

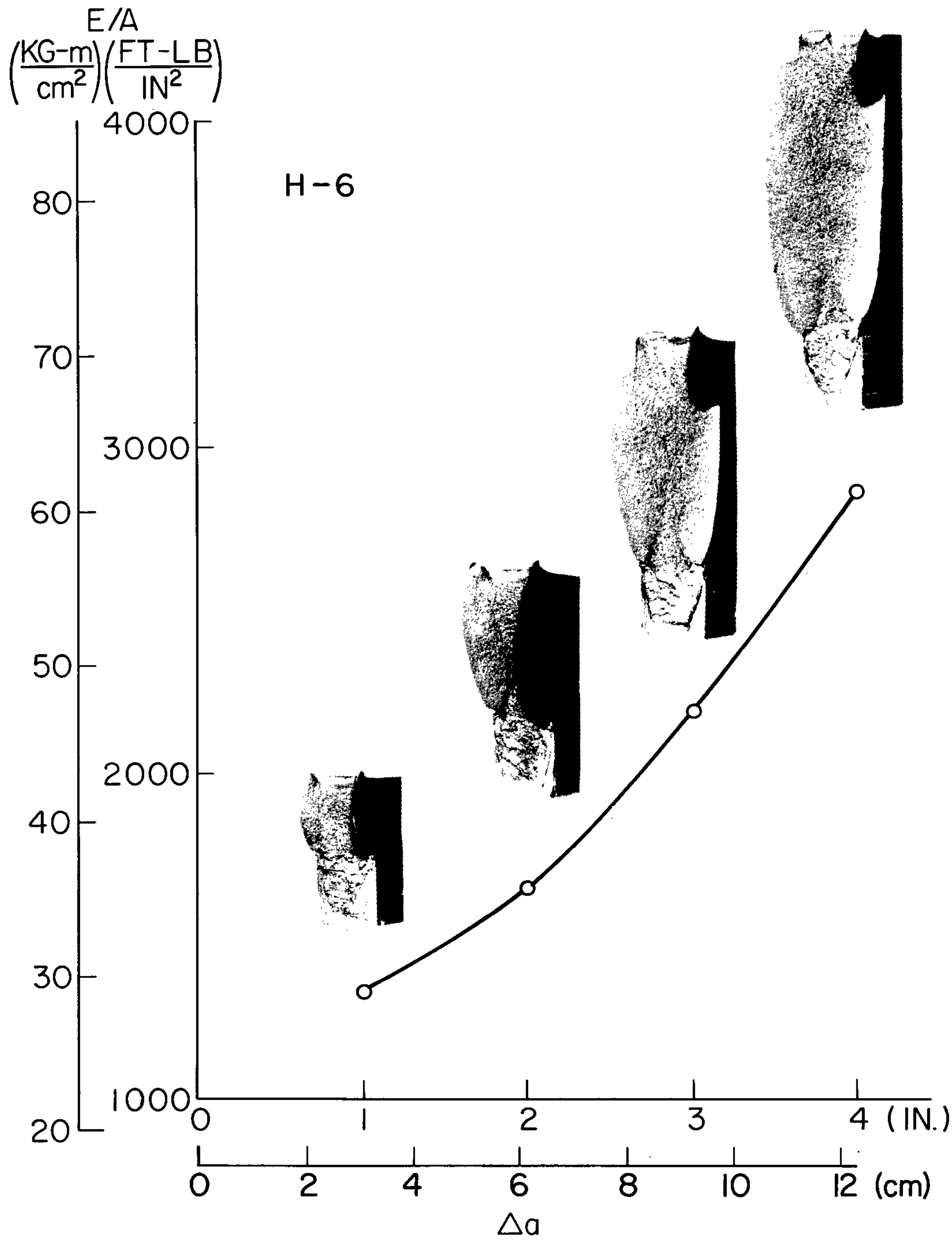

Fig. 8 - Fracture appearance transition and R-curve features for the high-shelf H-6 steel

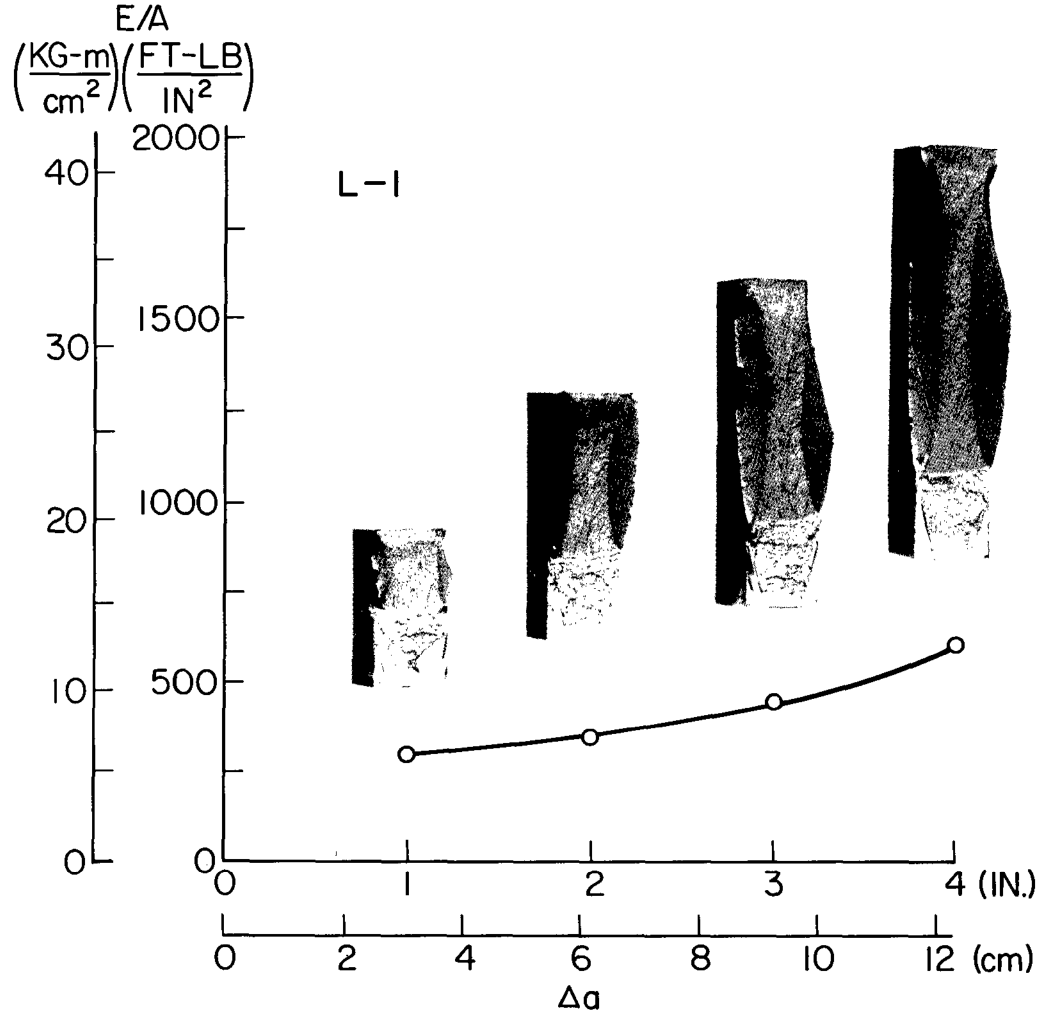

Fig. 9 - Fracture appearance transition and R-curve features for the low-shelf L-1 steel.

of 1/2, 1, and 2 in., respectively. The size of the plastic dimple at the plate surface increased with increasing crack extension.

Low-shelf L-1 steel—The dimples indicative of plastic enclave formation were not observable visually for this steel. Micrometer measurements would be required to measure the very small degree of through-thickness reduction localized to the crack tip plastic zone. Thus, very low values of input energy were sufficient to cause fracture extension. The crack extensions were 0.25 in. at 333 ft-lb, 0.40 in. at 500 ft-lb, 1.5 in. at 750 ft-lb, and complete fracture occurred at 1000 ft-lb.

A comparison of the results obtained from the two steels, Fig. 10, is made on the basis of the E-Δa relationship for the low-blow technique. The differences in the E values at the a_o points illustrate that the R curve rises from an intercept energy value related to the initiation phase. The energy required to initiate fracture extension in the

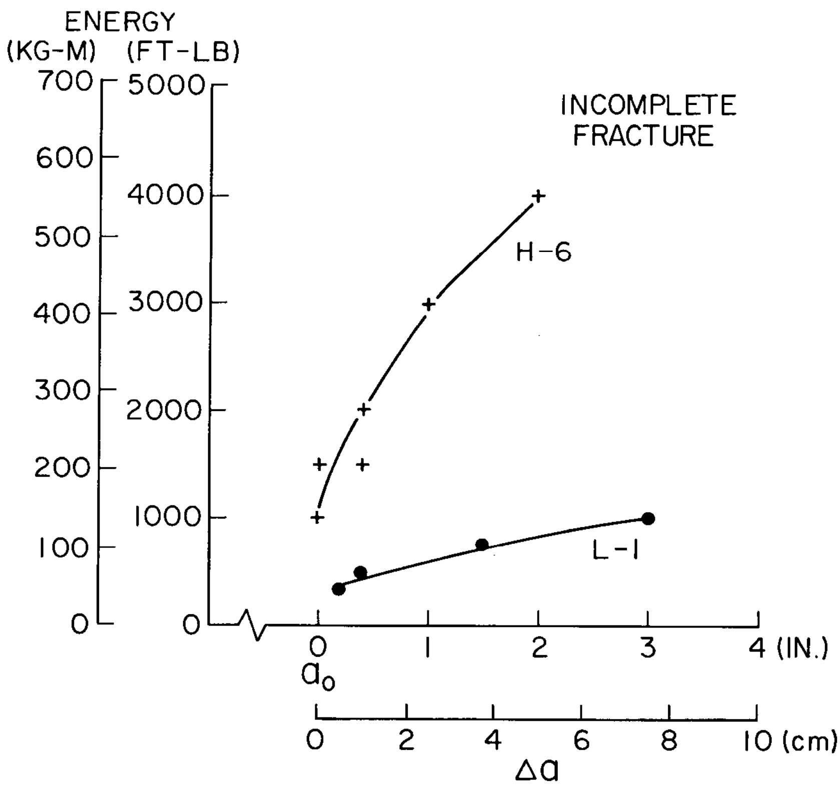

Fig. 10 - Summary of "low-blow" test data, illustrating the energy requirements for the first extension increment and for continued extension for the low-shelf (L-1) and high-shelf (H-6) steels. Note the dramatic differences in fracture extension resistance, representing very high and very low R-curve features.

H-6 steel exceeds 1000 ft-lb. This amount of energy is expended in formation of the plastic zone prior to the first extension increment of the fracture. Energy values in excess of this amount are necessary to cause continued extensions of the fracture. The increased energy is related to the formation of larger plastic zones (enclaves) as the fracture propagates. In contrast to this behavior, the low-shelf L-1 steel does not feature the development of a large plastic zone prior to fracture extension. For this reason, comparatively low amounts of energy were sufficient for the first extension increment (low intercept value). Continued extension required relatively small increase of energy because a plastic enclave did not evolve.

These physical aspects described above are evident from the photographs shown in Fig. 11. It should be noted that a 1000 ft-lb blow resulted in complete fracture of the low-shelf steel L-1. In contrast, approximately 2000 ft-lb was required to initiate the extension of a ductile tear for the high-shelf steel H-6, and 4000 ft-lb was required to cause a near-complete fracture. The size of the huge plastic zone (enclave dimple) developed by the high-shelf steel is indicated by the dashed lines superimposed on the photograph. In contrast, the low-shelf steel did not show a dimple, indicating that the plastic zone was restricted to a very small volume at the tear tip.

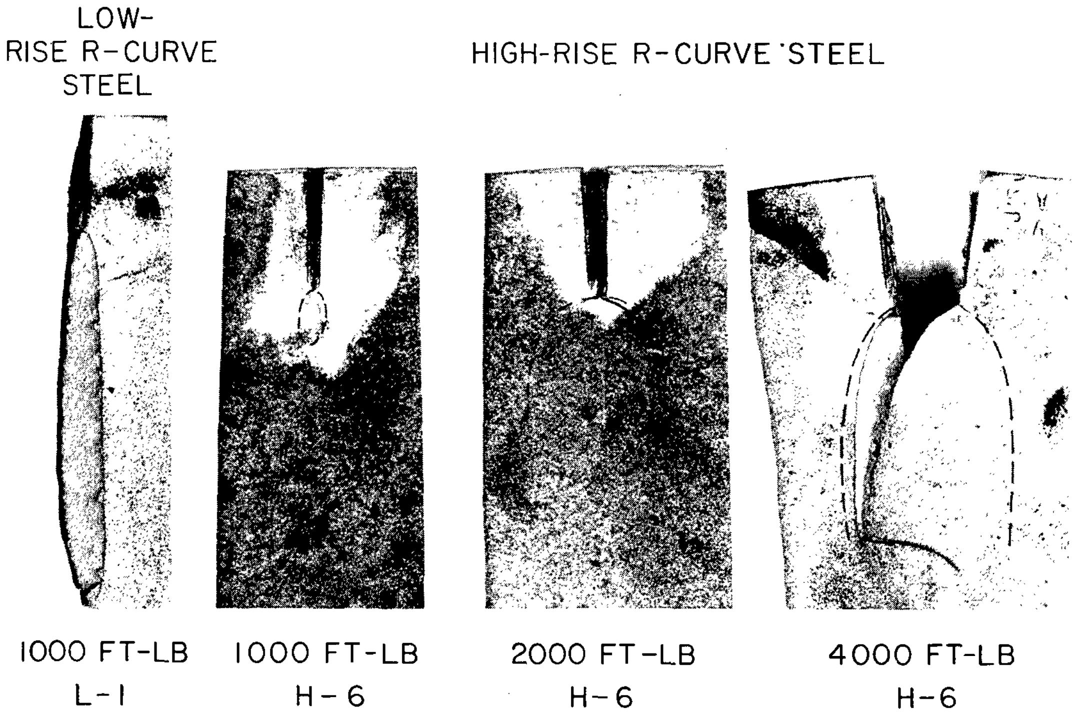

Fig. 11 - Physical features of the "low-blow" test specimens. Note that a 1000 ft-lb blow resulted in complete fracture of the low-shelf steel L-1. In contrast, approximately 2000 ft-lb was required to initiate the extension of a ductile tear for the high-shelf steel H-6, and 4000 ft-lb was required to cause a near complete fracture. The size of the huge plastic zone (enclave dimple) developed by the high-shelf steel is indicated by the dashed lines superimposed on the photograph. In contrast, the low-shelf steel did not show a dimple, indicating that the plastic zone was restricted to a very small volume at the tear tip.

The characteristic R curves (E/A vs Δa) for the eight steels included in this study are shown in Fig. 12. The relative level of the R curves as well as the slopes may be noted to rise in the general order of the DT shelf energy values plotted in Fig. 6. The R-curve relationships to crack tip blunting and plastic enclave features described for the preceding examples apply to the steels which show rising R curves.

A comparison of the H-7 steel with H-6 indicates identical R curves and significantly different values of yield strength. These aspects are independent parameters for different steels and for different orientations in the same steel. In this respect, reference is made to the wide variations in DT shelf energy characteristics for the same strength level that is represented by RAD summaries, Fig. 13 (4). The DT shelf energy value is directly related to the R-curve slope, i.e., steels of different yield strengths will feature the same R-curve slope if the DT shelf energy values are the same.

On the RAD of Fig. 13, a constant critical flaw size-stress level condition is denoted by a constant K_{Ic}/σ_{ys} ratio line; increases in yield strength require increases in K_{Ic} to maintain the ratio at a constant value. The slope of the ratio line with respect to the DT energy scale signifies that increased DT energy absorption is required to offset the effects of increased K levels resulting from increases in yield strength. Similarly,

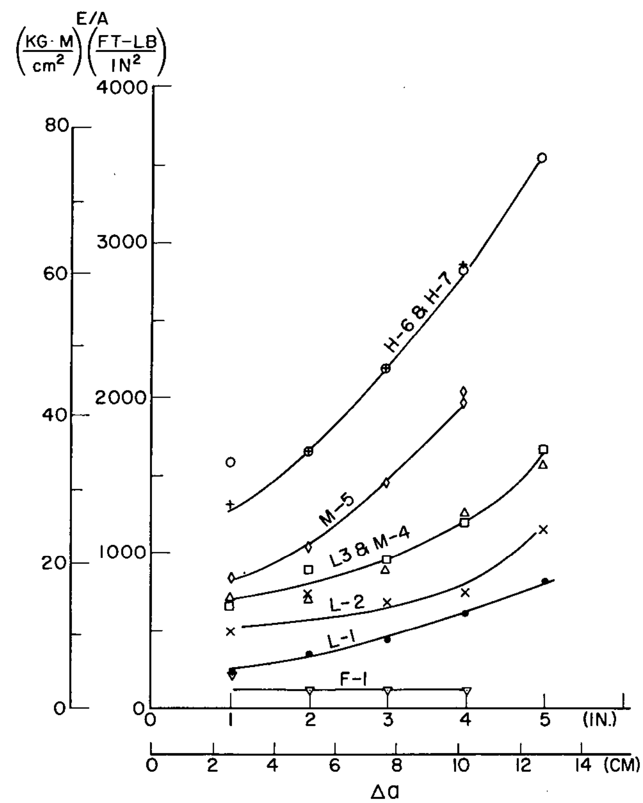

Fig. 12 - Summary of E/A vs Δa data which define the R-curve features of the various test steels. There is an increase in R-curve slopes and increased intercept values (first extension increment) with an increase in shelf level as defined in the RAD plot of Fig. 6.

there is a requirement for increased fracture extension resistance (R-curve slope) to offset the increased level of allowable plastic stresses (acting on a given flaw) which result from increasing yield strength. This requirement must be met by increasing the DT shelf energy value as a function of increasing yield strength.

In simple terms, the prevention of fracture extension for a specified flaw size will require increased R-curve slope (increased DT shelf energy) because of the increase of allowable stress levels which result from increased yield strength. The analytical definition of specific design requirements for fracture extension resistance (in terms of R-curve slopes or the equivalent DT shelf energy) must be related to flaw size, allowable stress level, and compliance characteristics of the structure. These relationships must be evolved by correlations with structural prototype tests, for reasons which are explained later.

Note that the significance of the DT data points must be related to section size. All DT data of Fig. 13 are for 1-in. DT specimens. If the 1-in. DT specimen is taken from a 2.5-in. plate, the appropriate ratio line which relates to the plane strain limit for the plate is 1.0. Table 3 defines the plane strain fracture toughness limits in terms of K_{Ic}/σ_{ys} ratios for given values of thickness. These thickness-related limits are plotted

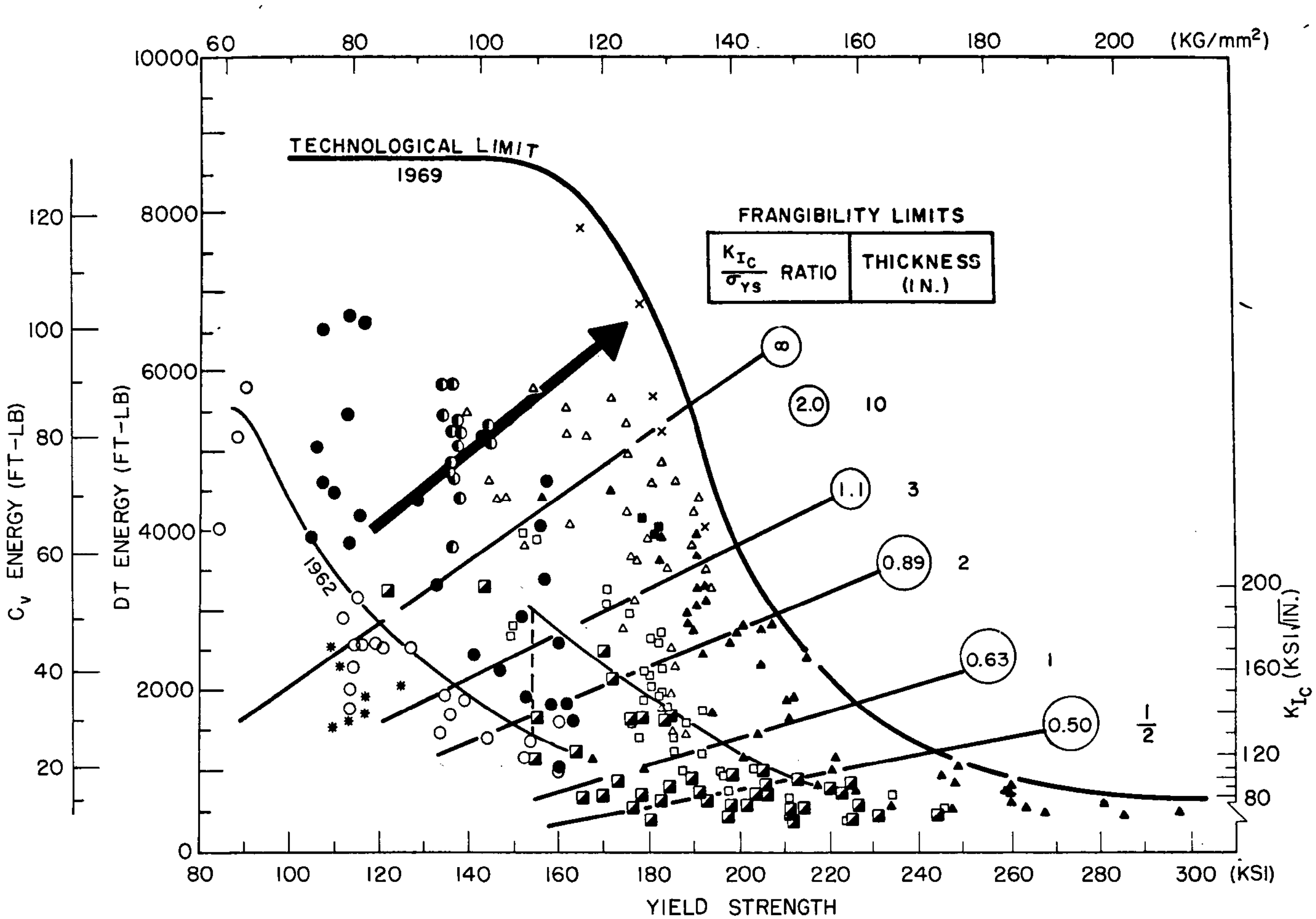

Fig. 13 - Summary of RAD data illustrating the wide range of shelf characteristics for steels of the same strength level. The technological line for 1969, as compared to 1962, indicates that the limit of attainable shelf properties has been increased dramatically (bold arrow) during this time by metal processing improvements (see Appendix A). The ratio lines represent the limit of plane strain for the specified thickness, as defined by Table 3. The infinity (∞) ratio notation indicates that plane strain cannot be developed above this line irrespective of thickness. Note the "shelf transition" that evolves as a consequence of increasing yield strength level. Above 200 ksi (140 kg/mm) all steels are of plane strain fracture type for thickness of 1.0 in. or greater.

as ratio lines in the RAD of Fig. 13. Constraint effects due to section size are analyzed in this fashion and represent a basic consideration in the use of the RAD. The degree of plane stress fracture toughness for the 2.5-in. plates should then be related to the energy values which lie above the 1.0 ratio line.

Table 3
Plane Strain Limits For Through-Thickness Cracks
Plate Thickness B ≥ 2.5 (K_{Ic}/σ_{ys})

Plate Thickness B (in.)	Plate Thickness B (cm.)	Maximum Ratio K_{Ic}/σ_{ys} for Plane Strain $(in.)^{1/2}$	Maximum Ratio K_{Ic}/σ_{ys} for Plane Strain $(cm.)^{1/2}$
0.5	1.27	0.45	0.72
1.0	2.54	0.63	1.00
1.5	3.81	0.77	1.22
2.0	5.08	0.89	1.42
2.5	6.35	1.00	1.59
3.0	7.62	1.09	1.73
4.0	10.20	1.26	2.00
6.0	15.25	1.54	2.45
10.0	25.4	2.00	3.18

ANALYSIS OF R-CURVE DATA

The R-curve forms of Fig. 2 are evident in the Fig. 12 data plots. An important feature of the *characteristic* form of these curves is that increases in the R-curve slope are related to increases in the intercept value, defined by the E/A value for the first extension increment (1 in.). Since the characteristic shape of the R curves is known, two data points may be used to establish the R curve for a given metal. Thus, it is not necessary to conduct extensive tests to plot the full R curve. Two points, derived from a plane strain DT-type test and a plane stress DT-type test, Fig. 2, are sufficient to establish the characteristic slope of the curve.

A curve-fitting analysis of the R curves was made by plotting the data on log-log coordinates, which results in the straight-line relationships shown in Fig. 14. The slopes of the lines vary only between 1.85 and 2.0 for these seven steels. If the slope is taken as approximately 2.0, a relation is inferred where the energy E varies as $E = R_p (\Delta a)^2 f(B)$. R_p is a constant that defines the position of the curve on the log-log plot, which is different for each steel, Δa is the crack extension, and the exponent 2 is the slope of the log-log plot. The f(B) term represents a function of the thickness B of the specimen. The R curves (E/A values) for the 1-in.-thick steels are related to this plot, Fig. 14, by dividing the E value by the fracture area of the specimen, i.e., $R = E/A = R_p(\Delta a/B)f(B)$.

These data all relate to a single value of thickness; establishment of generalized relationships, including the thickness B, requires tests involving wide variations of both Δa and DT test specimen thickness. The f(B) relationships are being established in a highly satisfactory manner; however, the discussion of this factor is beyond the scope of the present report. It appears that the f(B) term is approximately $B^{1/2}$.

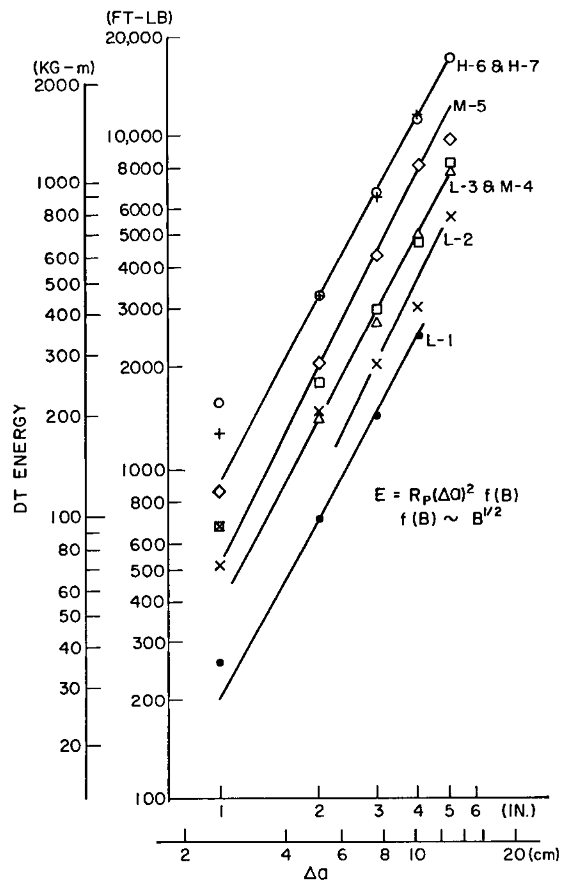

Fig. 14 - Log-log plot of Fig. 12 data. The nature of the relationships may be expressed by the formula noted in the graph, where E is the energy, R_p is a constant, Δa is the extension length, and f(B) or $B^{1/2}$ is the expression of the thickness (B) constraint effects as deduced from other studies. These relationships provide for definition of the R curve by two points, derived from the E values of the two DT test configurations.

The ability to express the characteristic R-curve features by an empirically derived equation, involving only specimen dimensions and a material-dependent constant R_p, is most valuable since it will permit characterization of materials in any thickness and resistance level by a single procedure.

The foregoing analyses do not imply that the resistance to fracture extension increases indefinitely with extension. The analyses apply only for the extension interval which involves the *fracture mode transition* from plane strain constraint at the crack tip to the characteristic plane stress mode of the metal. The R-curve rise which derives from this transition provides the "barrier" to fracture extension, and the analyses relate directly to this factor. Following completion of the fracture mode transition, the

R curve should "saturate", i.e., level out to a characteristic fixed level of resistance to continued extension. (See introductory discussions.)

The R-curve E/A plots do not level off because the fracture run is not extended significantly past the point of attainment of the characteristic plane stress fracture mode for the metal. Thus, the E/A value represents an average of the plane strain and plane stress portions of the fracture. In order to attain a leveling off, additional fracture extension would be required, so that the average E/A value would be determined primarily by the plane stress portion of the total fracture.

It is emphasized that the characteristic fracture mode is in fact attained by the standard DT specimen. This fact has been confirmed by extensive comparison of the fracture mode displayed on the Cylindrical Explosion Tear Test (with a fracture run of 8-in. for a 1-in.-thick plate) and the fracture mode attained by the DT test specimens. The fracture modes were found to be identical for both test procedures in all cases (4,5). These comparisons confirmed that the DT test provided a proper definition of the plane stress fracture features of the metal and decided the design of the test geometry. The relative slopes of the R curves determined by the described procedures provide an adequate basis for characterization of the fracture extension resistance. Additional refinements, such as following the E/A rise to saturation, would not provide significant improvement in the desired characterization of slopes, as will be described below.

Previous discussions have emphasized that information derived from the characterization of R curve slopes should provide for correlations with *prototype structural tests*. These correlations should result in empirical calculation capabilities for fracture-safe design based on critical plastic stresses or plastic strains for fracture extension. A logical question then arises: Is it possible to evolve such analytical procedures from first principles, i.e., from laboratory test measurement of critical plastic stresses or plastic strains for fracture extension, which are coupled directly to a mathematical analysis? If so, a case would be presented for waiting for the evolution of more sophisticated laboratory tests.

Unfortunately, a generalized analytical approach which would apply to all types of structures is not feasible, except as evolved by structural prototype testing. Generalized analytical approaches, based on first principles, run into complications of structural features which, per se, cannot be analyzed directly by mechanical principles. For example, a tensile-loaded plate structure will not behave in the same fashion as an internally loaded pressure vessel. The presence of flaws in pressure vessels may cause bulging (geometric instability); moreover, the energy available for fracture extension depends on the pressurization medium (gas or liquid), the diameter-to-thickness ratio, etc. For these reasons, it is necessary to analyze the structural response on a case basis. Such studies are being conducted for gas transmission lines and various types of pressure vessels. If a proper sequence of such tests is repeated for different generic structural configurations (flat plate structures, etc.), a generalized analytical framework keyed to simple laboratory tests should emerge.

For structural reasons related to energy release characteristics, it is not feasible to conceive the development of a laboratory test which performs a function beyond the definition of the R-curve slope. The closest modeling which can be achieved is that of the increased resistance to fracture extension. The prototype structural tests (which are not fracture resistance characterization tests) must extend the modeling process for the evolution of the analytical procedures.

Definition of the R-curve slopes provides information which relates to the intercept value (resistance to first extension) and the relative saturation value (resistance to indefinitely continued extension). Both of these aspects increase with an increase in the R-curve slopes. It is not necessary to define these aspects *specifically* for engineering purposes. The correlation intent is served by the definition of the R-curve slopes. Any attempt to provide such additional definition would complicate the laboratory test procedure to a degree that would obviate its usefulness *in specification and quality control.* The fracture research specialist will appreciate the significance of this statement because of an analogy to the problems of K_c testing for thin-sheet metals. With increasing ductility (R-curve slope increase), the size of flaws and sheets required for K_c testing increases to alarming proportions. The capacities of ordinary tensile testing machines and grips are quickly exceeded. The dimensions required for plates, say for 1 in. thickness, would be too large to serve as test specimens, except for metals of very low R-curve slopes.

Because of these practical considerations, it is concluded that the immediate research effort is best directed to two aims:

1. characterization of metals in terms of R-curve slope features and development of procedures for calculation of "size effects", and

2. structural prototype tests of the various (limited) generic types, such as tensile-loaded flat plate, pressurized cylinders, and bulge tear tests. These tests must include weldments so that weld and heat-affected zones can be considered, as well as the prime plate.

ENGINEERING SIGNIFICANCE OF R CURVES

Rising R curves of steep slope provide positive evidence that unstable fracture extension in the brittle mode is not possible for the section thickness B represented by the test specimen. Since the effects of increased section size are rapidly becoming understood, the R-curve slopes for specimens of small thickness (say 5/8 or 1 in.) can be translated to predictions of fracture extension characteristics for plate sections of greater thickness in engineering structures. R curves which are flat or of very low slope indicate that unstable fracture propagation is possible. If fracture instability is possible, then there is no need to consider the structural aspects of compliance—either rigid or compliant structures will be subject to fracture initiation at predictable values of K_{Ic} or K_{Id}, as applicable. For conditions of low slope, the K_c parameter may apply; however, there are no reliable procedures for analytical definition of the initiation conditions for this case.

Of equal importance is the classification of the significance (or not) of K definitions for fracture initiation. For a metal featuring steeply rising R curves, K parameters for fracture initiation are of no consequence, no matter how elegantly described as being K_x (where x is any nonstandard designation) or "lower bound" values. If the fracture resistance cannot be expressed as being a valid K_{Ic} or K_{Id} type, there is no analytical value to be derived at the present state of knowledge.

There is a wide gamut of potential engineering failure conditions which can involve geometric instability. In general, these are conditions such that fracture extension may develop, even for nonfrangible metals, as the result of high-compliance response to the load system. An example is the development of a flaw for internally pressurized vessels or piping of sufficient length to cause localized bulging in the flaw area (6, 7). The consequent plastic loads acting on the flaw ends can cause fracture extension for ductile metals. The difference in initial flaw length that can lead to such extension is related to the R-curve features of the metal. Very large differences in the critical flaw length (inches to feet) for initiating continued tear extension would be represented by major differences in R-curve slopes.

These aspects apply in a most important manner for gas transmission pipelines. In this case, the engineering consideration is the reduction in the fracture extension velocity, to the point that the gas pressure release occurs at a rate sufficient for unloading of the hoop stress acting on the propagating tear. Low-slope R-curve metals may be expected to permit relatively high rates of fracture extension, while high-slope R-curve metals should decrease this rate dramatically, leading to fail-safe conditions. The engineering problem is the definition of the adequate (minimum) R-curve features which provide for fracture arrest (by pressure release) for the specific diameter and pressurization level of the pipe. Correlations between full-scale burst tests and laboratory test definitions of R-curve features are required. While C_v shelf level values are being used for such correlations, more exact definitions should be possible by means of full-thickness DT tests in the proposed configurations. An additional advantage of the DT test is that it provides an exact definition of the temperature of transition to shelf levels for the thickness involved. The C_v specimen can define this point only by another correlation. The requirements for two types of C_v correlations introduces undue complexity in the analyses.

The use of high-strength commercial steels in ships poses questions of ductile tear extension possibilities. Commercial low-cost Q&T steels which are being considered may feature R curves of very low slopes. The high compliance of ship structures in amidship regions provides ideal conditions for fracture extension in such materials. It is reasonable to suspect the safety of such structural configurations and to consider utilizing metals of reasonable high-rise R-curve features for the critical amidship region. The general specifications for steels of these grades (grades A514-A517) cover a broad range of alloy types and are not definitive as to steel quality aspects which relate to shelf characteristics. Thus, the shelf features of these steels may vary over a wide range without a definable lower limit. A lower limit must be set to provide a significant degree of plane stress fracture resistance for the section size. Specification procedures for ensuring that this is the case are not being utilized at the present time. (See discussions in next section concerning C_v test.)

The engineering considerations of compliance characteristics and total available energy (for example hydraulic versus pneumatic loading of pressure vessels) must be included in analyses of the level of R-curve rise required of the metal. Low compliance and low total energy translate to adequacy for a metal of relatively low R-curve rise features. Conversely, high compliance and high total energy translate to requirements for high-rise R-curve features. The balance between these factors is not definable presently by direct analytical methods. Structural failure tests must be conducted to develop such correlations. The laboratory test, on which the correlation depends, must measure the R-curve characteristics in a significant, yet practical, manner. Moreover, the test procedures must be reduced to standardized practices.

In proposing the use of the two-configuration DT test procedure, a case is presented for the basic validity of the approach as well as of its standardization practicality. Any shortcomings at the present state of development relate to the lack of analytic procedures, involving plastic fracture mechanics, which enforces solutions by the correlation approach. Moreover, the structural aspects dictate that the correlation approach cannot by avoided, irrespective of test method, because the compliance and total energy factors defy exact analytical treatment. There are no other laboratory fracture test approaches which provide for measurement of R-curve features over a broad range of temperatures and strain rates. For steels the strain rate factor is an inescapable requirement because the R-curve slope should decrease sharply as the temperature falls to below the dynamic fracture shelf levels. The temperature point of this "fall-off" should be known exactly. Tests involving slow loading rates are inapplicable for strain-rate-sensitive metals. Such tests would indicate rising R-curve features for temperatures such that the dynamic extension of fracture would involve frangible characteristics.

The importance of R-curve features in relation to economic factors deserves mention. In special cases, directionality effects may be used as an engineering design tool. In such cases, an assessment should be made of the benefit to be achieved by controlled rolling and orienting the metal so that the "strong" direction is placed normal to the fracture extension path. The attendant increases in fracture extension resistance are not minor, but are of half order of magnitude scale or larger. Thus, directionality effects may serve as solutions to special problems without an increase in cost. An example is the possible use of low-cost straight-away-rolled steels in spiral orientation for the case of gas transmission pipelines. Another example is the use of such steels in fore-aft direction for ships. The importance of correct orientation should be clearly recognized.

INTEGRATION OF R-CURVE DEFINITIONS INTO THE RAD SYSTEM

Zoning of the RAD

The RAD system integrates mechanical and metallurgical factors by "zoning" in terms of both aspects. Definition of R-curve factors provide for additional analytical possibilities for these integrations, i.e., it provides for additional zoning in terms of structural aspects. The process of fracture-safe design requires total integration of all factors, either sequentially or directly. The feasibility of a direct, integrated analysis can now be demonstrated for the RAD. The discussions to follow will consider these aspects. It is important to recognize that metallurgical process control can provide steels of high-R-curve-slope features, if required for structural reasons. If the engineer appreciates these factors, there should be no aversion for payment of a reasonable premium for the purchase of intermediate-strength steels of required R-curve features. The concept of "buying strength at lowest cost" may be counter-productive and of catastrophic consequences. The metallurgical factors are well understood (see Appendix A).

The two types of DT specimen configurations provide for indexing the significance of the zonal region of the RAD which relates to plastic fracture. When the indexing is to ratio lines, or below, the R curve is flat because unstable, plane strain fracture extension follows the initial instability. Indexing to values of DT energy above the ratio lines region signifies a zone involving R curves of increasing slope. The engineering significance of the RAD is thus amplified, while retaining the inherent simplicity of a generalized diagram indexed by practical test procedures.

The metallurgical zoning of the RAD, which was discussed previously (2) in terms of significance to the ratio lines zone, can now be related to the aspects of fracture extension resistance for the zone above the ratio line for the thickness involved. Reference should be made to the "metallurgical corridors" described by Fig. 15 (2). The remarkable effects of furnace practice variables in controlling strength level R-curve relationships become apparent. For example, very large increases in fracture extension resistance may be attained in the yield strength range of 70 to 130 ksi (50 to 90 kg/mm^2) by the use of steels of higher corridor features. The corridors defined in the figure derive from alloy content, furnace, and deoxidation practice variables. Increasing strength causes a decrease in fracture resistance which is characteristic of the generic class. The corridors represent "steel quality" and, as such, are also "cost corridors," i.e., increased cost is involved in moving to higher corridors.

The R-curve indexing to the RAD adds the feature of zoning which includes the *type of structure*. For example, low-shelf regions of the RAD represent plane stress fracture resistance which may be adequate for relatively noncompliant structures. With increase in compliance features and total available structural energy, there is a need to select steels from the high-shelf locations of the RAD. Thus, the high-shelf regions

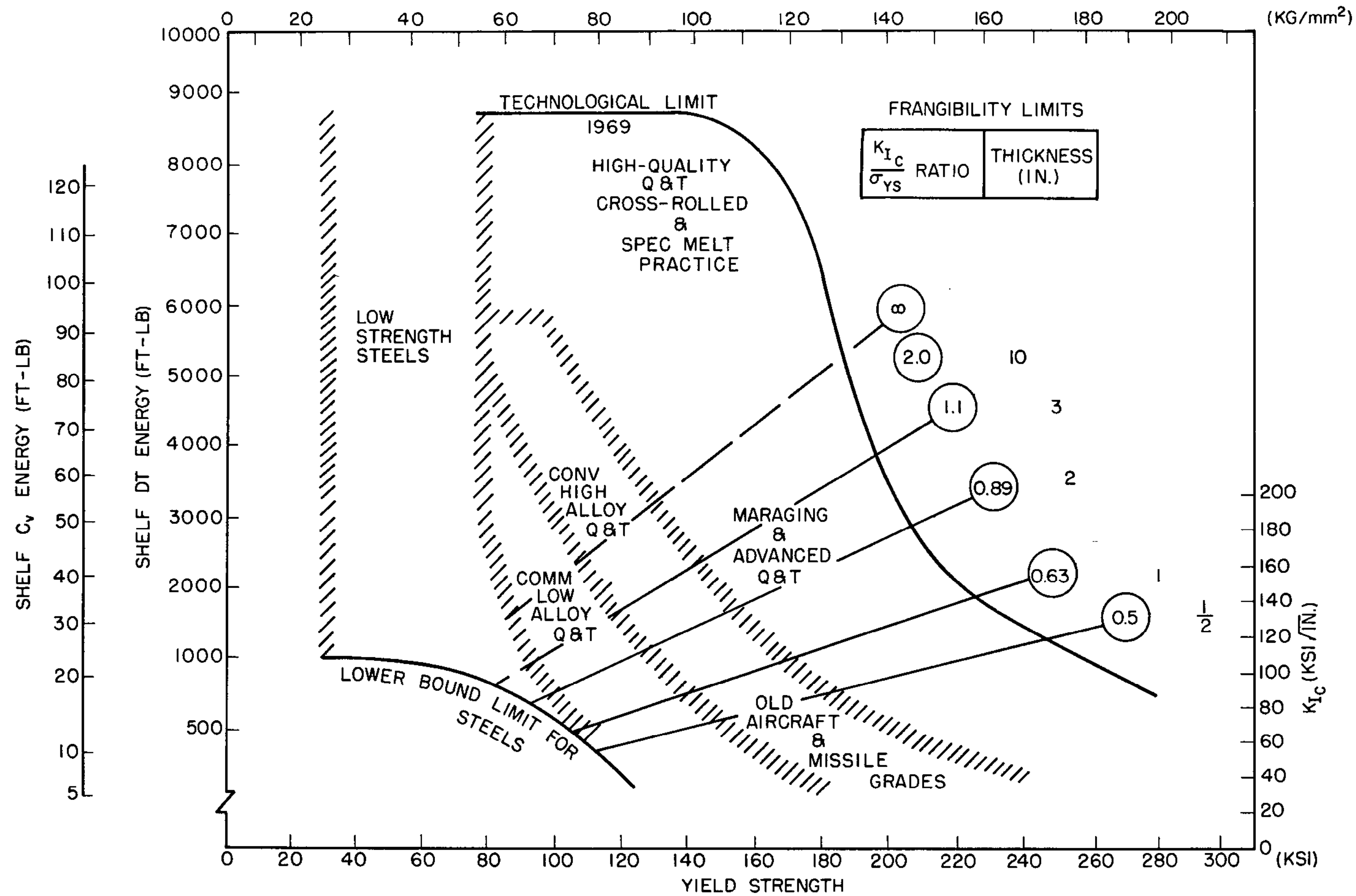

Fig. 15 - Metallurgical zoning of the RAD which defines the general effects of melting and processing factors on the strength transition. The three corridors of strength transition relate to metallurgical quality (void site density) which controls microfracture processes and, thereby the macroscopic fracture toughness of the metal. The location of generic alloy steel types are indicated by the notations.

may be defined as the high-compliance high-energy structural regime. Conversely, the low-shelf regions may be defined as the low-compliance low-total-energy structural regime. Regions below the ratio line, which applies to the specific section size, may be defined as the unstable fracture (for any type of structure) regime.

RAD Significance of C_v Scale

The C_v test provides the present primary international reference basis for characterization of the fracture resistance properties of steels. There is little use of this test for the nonferrous metals. The validity for this "metal type" separation in the use of the C_v test becomes apparent from comparison of the RAD plots for steels and the nonferrous metals (8, 9). The case for aluminum provides a good example for discussion—the primary alloys of engineering interest are all of relatively-low-shelf features. Therefore, difference in fracture extension resistance must be measured using tests which provide for fine distinctions. The C_v test results in low energy values which provide very little capability for such distinctions.

The long-term use of the C_v test for the case of steels has been for purposes of defining the transition temperature range for the low-strength-type steels. The toe-to-shelf transition range represents a very broad span of energy values for these steels. However, with increasing strength there is a decrease in shelf levels to the point that fine distinctions are again necessary, as for the case of the nonferrous metals. This aspect may be appreciated by reference to the "Commercial Low-Alloy Q&T" steel corridor of Fig. 15. Note that as the yield strength level of 80 ksi (55 kg/mm^2) is exceeded, there is a drop of attainable C_v *shelf* energy values. If the low-quality (bottom) region of the corridor is considered, it becomes evident that the C_v shelf values rapidly "compress" in the 25 to 15 ft-lb range. The parallel to the problems of using the C_v test for fine distinctions for the aluminum alloys becomes apparent. This is the same range which precluded fine-distinction use of the C_v test for the aluminum alloys. The same situation will apply to the steels of this type—the mechanical logic is inescapable.

If fine distinctions are not required, then there is merit in using the C_v correlation scale of the RAD. The extremely broad range of shelf levels, across the three metal quality corridors of Fig. 15, clearly provide for use of the C_v test. Because of the strength transition, there is a maximum strength level (specific to each corridor) above which fine distinctions are required, and the C_v test no longer serves a useful purpose. Thus, the RAD correlations of DT shelf energy to C_v shelf energy provide for the use of the C_v test with the described qualifications. However, there are other qualifications of serious importance that must be understood, otherwise the use of the C_v test can be of dangerous consequences. The most crucial of these is the transition temperature range question.

It must never be assumed that the C_v transition curve shelf denotes the location of the true temperature point above which shelf properties apply to the section size of interest. This assumption is reasonably valid only for the lowest strength mild steels of 0.5 to 1.0 in. thickness. It is not valid generally for thicker sections of these steels or for steels of higher strength, irrespective of thickness. It may be generalized that the C_v curve usually defines a transition temperature range *below* the true range for plate thicknesses of 0.5 in. or greater. Because of this aspect, such assumptions generally lead to inferences of fracture safety that are inappropriate and dangerous. The true location of the transition temperature range must be defined by indexing to other more definitive tests. For summary discussions of this question, the reader is directed to Ref. (2 and 4-7).

If the true transition temperature range is known from other tests, the C_v shelf value may be used for RAD plotting and analysis. It does not matter if the shelf location is at a lower temperature, because it is the shelf value, per se, that has mechanical meaning. However, the usual practice of conducting C_v tests at a fixed reference temperature (transition not defined) results in other problems. For this practice, there is no certain way to decide if the C_v energies represent shelf values. The intermediate- and high-strength steels feature fine metallurgical structures which do not give the clear indication of cleavage fracture typical of the low-strength steels. Because of the plane strain configuration of the C_v test, it is not possible to observe slant fracture characteristics which indicate shelf characteristics. In fact, there is very little change in fracture appearance over a very broad range of test temperatures from shelf to almost the toe region of these steels (10). The only certain way to ensure that the shelf energy has been determined is to test over a sufficient span of temperatures to define the C_v shelf region.

If all of these qualifications are met, it is possible to use the C_v test for significant engineering analyses. An example of such analyses is presented in relation to the ship structure discussion of the preceding section. This is the case of a highly compliant structure versus low-cost commercial Q&T steels. In the prior discussion, it was noted that "some of these steels may be barely above the frangibility limit of the section size." Conversely, many of these steels are considerably above this limit, and it is important to recognize the differences, particularly in specifications.

The engineer may now analyze these features by reference to known C_v *shelf* values for these steels. If such shelf values are available to him, it is suggested that he plot these in the RAD of Fig. 15. The survey experience of the authors indicates that for the yield strength range of 100 to 120 ksi (70 to 85 kg/mm) the population *density* should lie in the range of 20 to 50 ft-lb. There may be moderately lower or higher values if the full statistical range is evolved. The data relate to plates in the order of 1 in. thickness; thus the 0.63 ratio line of Fig. 15 may be used as a reference for the frangibility limit. The analyses should not be attempted for plates in excess of 1.5 in. thickness for these steels because of transition temperature features (brittleness) at ambient temperatures resulting from inadequate hardenability. The alloy contents are adjusted to provide subambient transition temperatures only for section sizes of less than 1.5 in., depending on type. This question is to be analyzed separately.

The RAD plotting shows that the frangibility limit is approached as the C_v value drops to below 20 ft-lb. At the 20 ft-lb value, the R curve should be similar to that of steels L-1 and L-2 of Fig. 12. At the high end of the quality range (40 to 50 ft-lb), the shelf may be considered of "M" (medium) type (see Fig. 6). The R curve should then represent slopes of the M-4 and M-5 steel types, Fig. 12. In fact, steel M-4 is representative of good quality for the steels (A514-A517 grades) under present discussion. These analyses indicate that these steels may range in R-curve characteristics from the M-5 level to the L-1 level, shown in Fig. 12. This is the broad quality range which is inferred by the C_v shelf values for this class.

The logic of analyzing the structural requirements should now be apparent. Differences in structural compliance should be considered in arriving at engineering conclusions regarding the quality level required of the steels which have been described above. There are broad varieties of structures for which the 20 to 30 ft-lb C_v shelf level may be considered an index of fracture-safe design adequacy. Conversely, this level may be inadequate for structures of high-compliance characteristics. Such decisions are the province of the designer and not the fracture research specialists. The role of fracture research should be to provide an analytical framework from which such decisions may be made by rational rather than intuitive or past-experience processes. Past experience may not be applicable as new materials are brought into economical service. Most importantly, we should not repeat the experiences of the past which involved solving the fracture-safe design problems of low-strength steels largely by failure analysis.

SUMMARY

A case has been presented for the redirection of fracture research to neglected issues of major engineering importance. These issues involve metals which are neither brittle nor highly ductile - otherwise defined as being of "low-shelf," "low-tearing-energy," or "low-plane-stress fracture toughness" features. The problems of such metals involve the relatively low resistance to fracture extension because of the low-energy absorption characteristics. The probabilities of failure increase with flaw size, applied stress, the compliance characteristics of the structure, and the total load energy acting on the structure. The metal-type structure-type relationships must be analyzed in order to arrive at satisfactory fracture-safe design solutions.

The basic parameter of importance to the safety of compliant structures is the specific fracture *extension* resistance of the metal. This parameter is defined by the R curve of the metal which relates the degree of increase in fracture extension resistance (R) with movement of the crack (or tear) away from the initial crack tip. The R-curve features of metals may range between the two broad extremes of nonrising and steeply rising. A nonrising R curve signifies a condition such that the resistance to fracture is entirely dependent on the first unit extension, i.e., initiation. After the first unit extension, there is no further increase in fracture resistance, and the fracture process is defined as unstable (fast-brittle fracture). A rising R curve signifies a metal which breaks down the initial plane strain constraint to plastic flow at the crack tip, in the course of fracture extension. Thus, the mechanical state acting in the course of fracture extension changes from plane strain to plane stress.

Plane strain signifies essentially nil through-thickness yielding (plastic zone size is small). Plane stress signifies some degree of through-thickness yielding, ranging from low to high order, i.e., small plastic enclave dimpling to huge plastic dimpling. Thus, the plane stress condition may range from the low-tearing-energy type (low-slope R curve) to high-tearing-energy type (high-slope R curve).

The significance of the R-curve slope is described in detail, including effects on crack tip blunting, effects on fracture appearance, and effects on the increase in load required for continued extension.

The most important consequence of increased R-curve slope is the effect on the energy that must be expended by the structure to extend the fracture during the period of change from plane strain to plane stress. The distances involved in the transition of mechanical states are in the order of several times the section size, depending on the R-curve slope. Large flaws, high stresses, and high-compliance structural features may be ineffective in breaking through the energy resistance barrier provided by a high-slope R-curve metal. Conversely, small flaws, high stresses, and high-compliance structural features may easily break through the energy resistance barrier provided by a low-slope R-curve metal. The objectives of the new research are to establish guiding principles which provide for solving the relationships between structural features and metal R-curve characteristics. These solutions cannot be evolved in the absence of test methods which define R-curve features.

Fracture mechanics tests define conditions for initial extension in terms of K factors. Thus, such tests cannot provide a definition of R-curve characteristics. Accordingly, there is a basic requirement for using energy-measuring test methods which index the fracture energy increase with crack (or tear) extension.

The DT test in the standard configuration provides sufficient crack extension distance to index the degree of change in mechanical constraint—plane strain at the crack tip to whatever degree of plane stress that is developed by the metal. Thus, the DT energy reading (as well as the fracture appearance) provides an index of the R-curve

slope. The standardized specimen is defined as the *plane stress DT configuration,* because the length of run allows the development of the plane stress state which is characteristic of the metal. If the metal is brittle and fractures in the plane strain mode, correlations may be made between DT energy and K_{Ic} or K_{Id} parameters. These correlations reflect the fact that while the plane stress transition was *allowed* by the specimen geometry, it did not *evolve* for reasons of intrinsic metal properties.

The basic virtue of the DT test is that it can index all degrees of transition in mechanical states. This feature also permits direct measurement of the R-curve features by reducing the length of fracture run. When the length of run is decreased to a distance equal to the specimen thickness, a close approach to flat fracture is developed because the plane strain state conditions dominate. The short-run version is thus defined as the *plane strain DT configuration.* The fracture energy-over-area (E/A) value for the plane strain configuration may then be compared to the E/A value for the standard plane stress configuration. The slope of the R curve is thus established by plotting the two values against Δa (crack run).

The primary purpose of this report is to introduce the subject of R curves and its significance to metal-type structure-type aspects of fracture-safe design. Thus, the presentation of research experiments is limited to illustrative examples of R curves determined by various DT specimen techniques. Topical reports covering additional information will follow.

The illustrative examples focused on the selection of test steels from various locations in the RAD. The selections were made on the basis of the spread of strength levels and a spread of shelf characteristics. As should be expected, the following results emerged:

1. High-shelf steels, located in the top region of the RAD, demonstrate steep R curves. This should be expected because the high-shelf RAD location signifies a fracture extension transition to high-energy intensity plane stress.

2. Low-shelf steels, located barely above the ratio level limit for plane strain for the section size (0.63 for 1 in. thickness), demonstrate very slight R-curve rise. This should be expected because the transition involved is to a low order of plane stress—barely above the plane strain (brittle) value.

3. Intermediate-shelf steels demonstrate R curves of intermediate rise features.

The R-curve indexing capabilities of the DT test adds another dimension to the use of this versatile test procedure. Added meaning is provided for the FAD and RAD systems of fracture-safe design analysis. These systems were previously of primary importance for analysis of conditions relating to brittle fracture, or for its preclusion. With the additional analytical potential evolving from R-curve interpretations, applications may now be made for conditions of semiductile or ductile fracture, i.e., plane stress. In particular, the RAD system fits especially well to analyses of low-shelf (low-tearing-energy) metals in relation to structures of high-compliance features. In simple terms, structural requirements involving increasing degrees of fracture extension resistance may be met by moving to metals located in higher regions of the RAD.

Knowledge of the R-curve slopes for the various locations of the RAD represents a "third dimension" to this integrated reference system. For example, steels which were described as being "barely above the ratio line for the thickness involved" would be illogical candidates for pressure vessel or pipeline construction. The question of "how high above the ratio line is enough" should find its answer in detailed definition of the R-curve slopes using the two-configuration DT test procedure.

It may be argued that such definitions would require analytical capabilities for defining section size effects and critical fracture strains. This is true, and such relations are being evolved by a deliberate course of investigation of such factors. At this point in time, there is no pretense that a full analytical system has been evolved. However, there is ample justification to claim an open road ahead for evolving such a system, based on simple test procedures and easily understandable analysis diagrams.

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APPENDIX A

METALLURGICAL FACTORS RELATING TO R-CURVE FEATURES

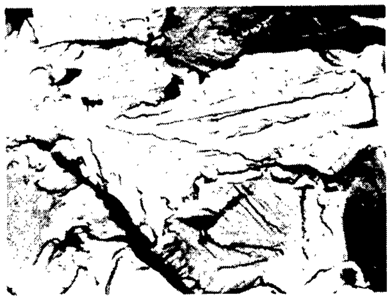
The mechanical constraint which "acts on the metal" at crack tips is a function of the crack size, i.e., the crack dimensions. For fracture extension in a plate, the crack front dimension is determined by the section thickness. Accordingly, the mechanical constraint level increases with an increase in section thickness.

The basic cause for the "breakdown" of the plane strain mechanical state which exists at the tips of the sharp through-thickness flaws is the intrinsic metallurgical ductility. Crack extension, which first evolves under the plastic flow constraint of plane strain, breaks down to plane stress with extension for reasons of metallurgical ductility. For crack extension, the metal grains must be strained to the degree required for rupture of the plastic zone. The critical rupture strain ϵ_c may be high or low depending on the microstructural features of the metal. The plastic zone size will then be correspondingly large or small. If small, the constraint level imposed by the section size continues to act during the extension process. If large, the constraint level is quickly broken down, and plane stress (through-thickness yielding) dominates. Thus, it is the metallurgical feature of the metal which determines the degree of plane strain to plane stress transition, i.e., the slope of the R curve and, thereby, the shelf level.

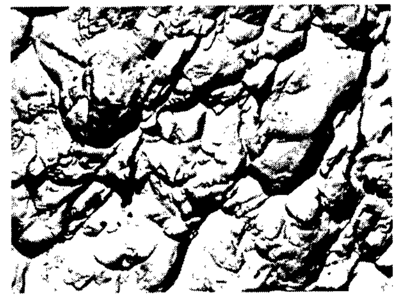
For steels, the temperature transition for the shelf condition is entered gradually as the microfracture mode of the individual grains attains conditions of high cleavage-fracture ductility and then fully ductile rupture. It is not the result of simply eliminating the last signs of cleavage. The ductile rupture process evolves by the opening up of small voids between grains, and particularly at sites of nonmetallic inclusions. The metal bridges between these sites are elongated as tiny tensile specimens, which finally rupture in a progressive (slow) ductile mode. Because of these features, the fracture process is defined as void coalescence (void growth), i.e., the development and enlargement of microscopic voids.

The fracture appearance at the shelf is termed "fibrous" (silky) when observed by eye and "ductile dimple" when observed at high magnification, as shown in Fig. A1 (right). The dimples represent the sites of microscale tensile rupture. At temperatures considerably below the shelf, the fracture process involves pure cleavage of the individual grains. The appearance to the eye is one of tiny, shiny facets. The cleavage of single grains is clearly visible at the high magnification shown in Fig. A1 (left).

The metallurgical factors which determine the specific temperature range of the lower half of the transition are different from those that determine the ductility level attained at the shelf. The temperature transition range is controlled by microcrack incubation processes, i.e., the genesis and enlargement of grain-size-scale cracks. The microcracks represent cleavage sites of individual crystals which crack preferentially, or the cracking of brittle metallic phases such as carbides. Grain size, the size and distribution of carbide phases, grain embrittling effects of solute elements such as P, N_2, O_2, etc., have a potent influence on microcrack formation. These effects are well known to the metallurgist and are used to suppress microcleavage and to favor slip processes. The transition temperature range is thus shifted to lower temperatures.



CLEAVAGE



DUCTILE DIMPLE

Fig. A-1 - Features of cleavage and ductile dimple (void growth) fractures

The level of shelf ductility is highly sensitive to the relative cleanliness of the steel. The presence of many sites of void nucleation due to nonmetallic inclusions promotes easy rupturing leading to "low-energy tearing." Since metal-forming processes result in preferentially aligning the nonmetallic constituents, a steel plate or forging will feature directions of low and high tearing resistance. Fracture in the direction of primary rolling will indicate "weak" properties as compared to the transverse or "strong" direction. For low-strength steels the weak direction of the commercial product does not ordinarily present a problem of excessively easy tearing. This is due to the high inherent ductility of the grains which form the bridges between the voids nucleated by the nonmetallic particles. With increasing yield strength this feature of high grain ductility is progressively decreased, and the presence of nonmetallic phases (high void site density) serves as an additional inhibiting factor on the effective ductility limit of the grain aggregates.

The metal bridge ductility and void site density aspects also apply to nonferrous metals such as aluminum, titanium, etc. Increasing strength level decreases metal bridge ductility and increasing void site density provides for the early development of void growth at low levels of strain. Thus ϵ_c is lowered by these factors, as for steels.

RAD summarization of strength-shelf relationships for aluminum and titanium are provided in Refs. 1, 8, and 9.

APPENDIX B

FRACTURE MECHANICS ASPECTS OF R CURVES

The principle of equilibrium of the work and energy values involved in fracture processes was applied by Irwin* and Srawley and Brown† to model the instability of cracks in elastically loaded bodies. The basic features of the balance between the work $\mathcal{G}$ of the externally applied stress field and the characteristic resistance R of the material to fracture are illustrated in Fig. B1 for the simple case of a two-dimensional body with a flaw of length 2a residing in an elastic tensile stress field. The term $\mathcal{G}$ is defined as the strain energy release rate with crack extension per unit length of crack border, or the crack extension force. R is the crack extension resistance of the material at the crack tip opposing $\mathcal{G}$. The strain energy produced by the stress field is represented by the straight line through the origin, while the slope of the line indicates the magnitude of $\mathcal{G}$. Characteristic R curves for different materials are illustrated by the R traces for this simple case; however, the shape of the R curves is influenced by geometrical considerations of the body, including flaw length, specimen width, thickness, stress state, etc.

The critical point in the energy balance system is when $\mathcal{G}$ and R are equal, which is visualized as the point of tangency for the two curves. This is the critical value of $\mathcal{G}$, which is denoted $\mathcal{G}_c$. The implication of the tangency is that an excess of the strain energy $\mathcal{G}$ to sustain the fracturing process is available, and therefore the fracture will propagate. For this idea to be meaningful, the fracture, once initiated, must be self sustaining (unstable). At $\mathcal{G}$ values less than $\mathcal{G}_c$, R is higher than $\mathcal{G}$ and crack initiation cannot occur due to the insufficient driving energy. The R curve for extremely brittle materials, such as glass, allows for no increase in R with crack movement. The other R curves of Fig. B1 are representative of many real metals which tolerate a very small degree of crack movement without fracturing. The R curves for materials which fracture elastically must, by definition, reach a point where R does not increase with increasing crack length; this is not the case for ductile metals. Higher levels of $\mathcal{G}_c$ are required for the fracture of materials with higher characteristic resistance R, as shown in Fig. B1.

For the maximum-constraint plane strain condition, the critical crack extension energy is denoted by $\mathcal{G}_{Ic}$. Basic equations of linear elastic fracture mechanics (LEFM) relate the critical $\mathcal{G}_{Ic}$ value to the elastic stress and flaw size conditions necessary for fracture. These equations are usable in the practical sense only for the case of plane strain ($\mathcal{G}_{Ic}$), because of a strong dependence of $\mathcal{G}_c$ on specimen dimensions, as well as basic materials properties. For plane strain, $\mathcal{G}_{Ic}$ is related to the critical stress intensity factor K_{Ic} by $K_{Ic}^2 = E\mathcal{G}_{Ic}$ where E is the elastic modulus.

K_{Ic} is a useful index of resistance to fracture that applies only for the nominal elastic stress, plane strain case. Under these conditions, K_{Ic} is an invariant property of

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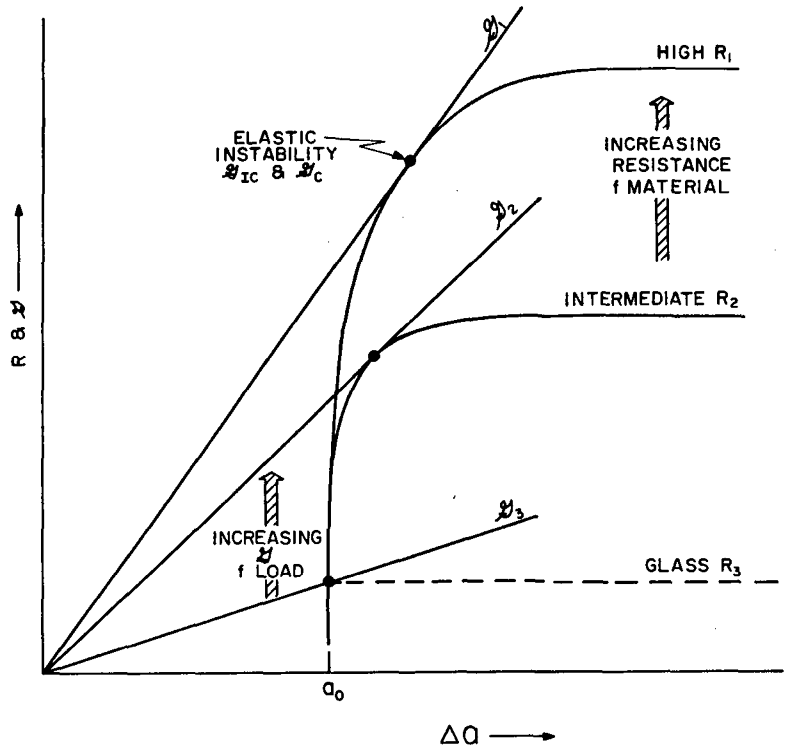

Fig. B1 - Fracture mechanics definition of R-curve features in terms of rising $\mathcal{G}$ to the point of instability ($\mathcal{G}_c$). The mathematical analyses apply for the case of elastic loading, but the basic concepts may be extended to visualize R-curve aspects in plastic fracture.

the material which relates the nominal stress and flaw size for fracture. A typical expression is

$$K_{Ic} = \frac{1.1}{\sqrt{Q}} \sigma \sqrt{\pi a}$$

where a is the flaw length, σ is the stress, and Q is a flaw geometry parameter. This example is for the case of a semielliptical surface flaw in an elastic tensile stress field. Other expressions are available to describe different flaw and loading conditions. The practical limit on the use of LEFM is dictated by thickness-constraint considerations. The upper limit of strict applicability of these principles is given in terms of thickness by $B \geq 2.5 (K_{Ic}/\sigma_{ys})^2$, with dimensions of minimum crack depth and length of crack run scaled to the B dimension. The analytics apply for the plane strain case because the equations are only required to describe the first extension event of fracture. A flat characteristic R curve shows that catastrophic failure will follow crack initiation.

When the limitations on dimensions of thickness and crack depth are exceeded, even for the elastic loading case, the K parameter is not free of geometrical influences, and the equations are not applicable. Thus, the K_c and $\mathcal{G}_c$ terms, which include all conditions other than plane strain, have no practical value in terms of ability to accurately predict fracture conditions. The loss of analytical exactness is caused by the rising R curve, which does not permit crack extension without continuous increases in energy. This feature of R renders determination of the critical fracture extension point difficult, if not impossible.

For the inelastic, plastic fracture condition, the *conceptual* approach to understanding fracture processes in terms of work and energy parameters remains valid, even though at present it is too complex for precise analytical treatment. Furthermore, the transition from brittle to ductile fracture modes can be regarded in terms of characteristic R curves and the corresponding increases of energy necessary to overcome the increased R. A greater degree of complexity is introduced for ductile metals due to yielding of the material. This fact necessitates the introduction of new methods and terminology to describe fracture resistance for inelastic conditions.

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13. ABSTRACT

Requirements for new directions in fracture research emerge from considerations of the basic lack of applicability of K parameters for definition of the fracture extension resistance of nonfrangible metals. New research is required into factors relating to the increase in plastic work energy resistance defined by R curves. The urgency of such studies evolves from the increasing use of metals of low-intensity plane stress (low-shelf low-tearing-energy) characteristics in structures of high-compliance features. A case is presented for the mutual consideration of metal-type structure-type relationships in fracture-safe design. Present fracture-safe design practices do not include a rational approach to this question.

The report provides an introduction to these considerations in terms of extension of fracture mechanics concepts, as well as metallurgical factors and engineering practices. The importance for understanding the interaction of these factors cannot be overstated, and considerable emphasis is placed on introductory aspects. Data presentation of R-curve research is limited to illustrative examples, which document the reality of fracture extension processes in determining conditions for structural failure. The report is intended as a precursor to topical reports on the subject.

A rationale is presented for the use of the Dynamic Tear (DT) test in standard and modified configurations, which provide for definition of R-curve features. Indexing of the R-curve features to the Ratio Analysis Diagram (RAD) adds new dimensions to analytical capabilities of this system. The integration of mechanical, metallurgical, and structural aspects which emerge should provide for significant advances in treating the fracture-safe design problems of nonfrangible metals and compliant structures.

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Fracture-safe design Fracture strength Fracture tests Metallurgical engineering Mechanical tests Ductility Cleavage Microstructure Structural steels Interpretations of fracture tests Interpretations of fracture mechanics theory to engineering design Engineering fracture mechanics						