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THE USE OF LINEAR ELASTIC FRACTURE MECHANICS IN VIKING PRESSURE VESSEL DESIGN

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ABSTRACT

Fracture mechanics methodology has developed rapidly over the past 10 years. Although not as yet sufficiently developed for the treatment of complex structures such as aircraft, it is believed that fracture mechanics can provide a sound basis for the design of simple structures such as pressure bottles or tanks. Consequently, the Viking Project has adopted its use for design of all pressure vessels on the Viking spacecraft to assure the long life under sustained pressure necessary for the trip to Mars.

INTRODUCTION

Fracture mechanics is a technology which has been developed principally in the last 10 years as a result of many unanticipated failures of structures during proof test or in service operation. More specifically, examination of structural components that failed unexpectedly have indicated that the failure origin was a small crack or cracklike flaw. Also, such failures were normally characterized by the absence of a large amount of plastically deformed or yielded material. A commonly cited example is the 260-inch-diameter steel (250 grade maraging steel) rocket motor case, which failed during test at a stress less than half of the design yield stress. The failure origin was traced to a small internal flaw in the heat-affected zone of a repair weld (Ref. (1)). Many other examples of brittle failure could be cited including those in tankage for the Apollo programs.

The study of brittle fracture and the development of test methods on a systematic basis was really started with the formation of a special ASTM Committee a little over 10 years ago, at the suggestion of the National Academy of Science and the Department of Defense. Since that time, test methods have been highly developed and quantitative measures of fracture toughness have evolved. Unfortunately, the technology is not sufficiently advanced to handle many of the practical problems facing designers. The F-111 and the C5A, for example, have problems with failures associated with crack growth. At the present time, reliable methods are only beginning to be developed for treatment of complex structures such as these under the highly complex loading conditions that they experience. However, for the relatively simple structure of a pressure bottle or tank, such as are found in the Viking spacecraft, the methodology is rather well in hand. The present discussion, then, is confined to that fracture mechanics methodology that is based on the work of Griffith and Irwin, and specifically as it is applied to the design of pressure vessels on the Viking spacecraft (V-S/C).

DISCUSSION OF FRACTURE MECHANICS

The basis for fracture mechanics is the fact that all structures have flaws (Fig. 1). The flaw size may be too small to detect or too small to affect the strength of the structure. However, a flaw can grow in size under repeated loading and it may grow under sustained load, particularly in a corrosive environment. In the past, traditional design methods were adequate because design allowables were low and the materials used were ductile, tolerant of flaws, and insensitive to environment.

For spacecraft, structural weight is a critical problem. This situation has led designers to increased design allowables through use of newer high-strength materials. However, many high-strength materials tend to be brittle and have lower fracture toughness. Low fracture toughness means the material is less tolerant of flaws. Also, the environments are more aggressive than in the past. In the past, failures were characterized by large amounts of plastic deformation or yielding, more nearly a plane stress condition. Brittle fracture, however, is characterized by only small, if any, plastic behavior - essentially a plane-strain condition. However, as will be shown later, this is dependent on the material and material thickness.

The goal of fracture mechanics is to provide a quantitative measure of resistance to unstable crack propagation. This measure is derived from consideration of the elastic stress field surrounding the crack. Figure 2 shows the simplest formulation of the problem (Refs. (2), (3)). The sketch shows the elastic stress distribution along a line in the path of the crack in an infinite sheet subjected to uniformly distributed stress. The stress distribution is given by the equation shown on the figure where a is the half length of the crack and r is the radial coordinate of any point in the sheet. Because the crack is sharp, the calculated local stress distribution contains a singularity. The numerator of the second term, $S\sqrt{\pi a}$, measures the mathematical strength of the singularity and has been designated the stress intensity factor, K. The basic assumption in fracture mechanics is that unstable fracture occurs when K reaches a critical value designated K_c (sometimes called fracture toughness).

Elastic theory predicts an infinite local stress at the crack tip for any loading on the part and leads to the use of a stress intensity factor rather than a simple concentration factor. Since the analysis is based on elastic theory, it applies only to brittle materials or those specimens having small enough plastic zones so that plane-strain conditions exist at the crack tip. The value of K_c, however, is a measurable quantity, since it depends only on the stress at which a test specimen fails and the length of the crack when it becomes unstable.

There is presently no known way to account precisely for the plasticity in the zone ahead of a crack. Also, a laboratory test specimen is seldom completely in either plane stress or plane strain, but rather some proportion of both. This is illustrated schematically in Figure 3 based on data from Ref. (4). The solid curve shows values of K_c such as are obtained from tests of specimens of varying thickness for a given material. As can be seen K_c decreases as specimen thickness is increased and can reach a minimum value. The inset shows the cross section of the fracture surface. The dashed curve shows the proportion of flat surface to the thickness. The minimum value of K_c is labeled K_{Ic} and corresponds to a nearly completely square fracture suggesting that fracture was accompanied by very little plastic deformation. This fracture condition is characteristic of the plane-strain mode of failure. The value of K_{Ic} is the plane-strain stress intensity factor at the critical condition of initiation of rapid fracture and is generally termed the fracture toughness of the material. In fact, it is accepted as a material property. For thin specimens, the stress state is more nearly plane stress. Fracture mechanics has not been developed so that the sloping part of the curves can be treated with confidence, and most emphasis has been placed on determining the minimum value of K_{Ic}.

Figure 4 shows one way that fracture toughness data are obtained (Ref. (5)). Specimens of the material, in this case 6Al-4V titanium, are made containing a surface crack of a given size. It is this type specimen that will be used in obtaining the basic fracture data for the Viking pressure vessels. It is loaded until it fails at some stress level. The symbols are data points for many such specimens with varying crack size. No attempt is made to characterize the curve between yield and ultimate in equation form. Below the yield stress, the data are fitted with a curve according to the equation shown. This is the same equation that we had earlier in slightly different form. By varying the value of K_I in the equation, a critical value is found which fits the data as shown. In this case the K_{Ic} value is 56 ksi $\sqrt{\text{in.}}$

Many different type specimens are tested in different ways, depending on the requirement of the application for which the data will be used. These include fatigue-cracked bend specimens, crack-line loaded specimens, edge-cracked sheet specimens, and fatigue-cracked round notched-bar specimens.

Another important consideration is that flaw growth can result from cyclic loading and/or from sustained loading in a hostile environment. Data from fracture specimen tests then must be obtained to predict the number of cycles or the time the vessel must be under sustained pressure for an initial flaw to grow to critical size.

Figure 5 shows that for a given environment and cyclic-loading profile, the cycles to failure depend primarily on the initial stress intensity K_{Ii}, that is, the stress intensity for the initial size crack as compared to the critical stress intensity K_{Ic} (Ref. (6)). The material is again 6Al-4V titanium. The data were obtained by cycling specimens with different size flaws at different stress levels. Both the best-fit curves and the 96% probability, 99% confidence level curve are shown.

Figure 6 illustrates the fact that flaw growth can occur under sustained loading. The ratio of the initial stress intensity, K_{Ii} to K_{Ic} is shown as a function of time. The slide also shows the most important characteristic observed in all sustained-load flaw growth experiments performed to date. That is, the existence of a threshold stress-intensity level for a given material in a given environment. Above this level, flaw growth can cause fracture if the load is sustained long enough. Below it a flaw will not grow no matter how long the load is sustained. This threshold, then, is the key to the design of safe pressure vessels that must sustain load for long periods of time. Values of K_{TH}/K_{Ic} show a very marked dependence on environmental characteristics (media and temperature). Shown on the slide are values for a titanium forging with a yield stress of 160 ksi for two different fluids at room temperature. In nitrogen tetroxide the K_{TH}/K_{Ic} ratio is 0.83. However, with methanol K_{TH} is less than one-fourth the value of K_{Ic} (Ref. (6)), a potentially disastrous situation for a titanium methanol container designed by traditional methods.

In obtaining values of K_{TH} for the Viking Spacecraft, environmental effects will be carefully considered. For example, in the Orbiter, the oxidizer tanks contain N_2O_4. This fluid will contain small amounts of NO and, surprisingly, at least a certain amount is desirable. An increase in the amount of NO contained in N_2O_4 fluid from 0.32% to 0.63% can increase the value of K_{TH}/K_{Ic} for 6Al-4V titanium by 8%. On the other hand, an increase in the operating temperature can decrease the value of K_{TH}.

The next two figures show the most important aspect of fracture mechanics and that is how it can be used to guarantee the life of a pressure vessel by proof testing.

Figure 7 is similar to Figure 4. The value of K_{Ic} will have been determined from the tests described. The test specimens will be of the same batch of material the tank is made of, the same heat, the same thickness, and in the same environment the tank will see. They will include welds and even specimens cut from excess material in the flanges of the tank itself. The proof test provides one highly important piece of information. If the tank survives the proof test we know that if a flaw exists in the tank it can be no bigger than the value a_i. This crack size then is less than the size of crack that will cause failure at the operating stress level. Using this size and the operating stress, the value of K_{Ii} is computed. It should be noted that, if for some reason such as an improperly welded seam, a local value of K_{Ic} exists in the vessel that is lower than the value of K_{Ic} obtained from specimen tests, the proof test results are still valid. Either the vessel fails in the proof test or any flaw in the local area of lowered fracture toughness must be even smaller than a_i. Hence the value of K_{Ii} relative to K_{Ic} is not changed.

Knowing the maximum size flaw that can exist in the tank as determined by the proof test, and the value of K_{Ii} as determined for the operating stress, the life of the vessel is then determined as shown on Figure 8. From the experimentally determined curve for the tank material, the permissible life is given. Of course, the procedure may be reversed to determine the relation between proof stress and operating stress that will assure sufficient life.

For the Viking spacecraft, the pressure vessels will see only a few cycles of loading and sustained load flaw growth becomes of paramount importance because of the long travel time to Mars. Consequently, the relation between proof and operating stress must provide the assurance of long life under sustained load.

This paper has reviewed only the basic concepts of fracture mechanics needed to permit discussion of its use in design of the pressure vessels on the Viking spacecraft. A more general review is given in a recently published NASA space vehicle design criteria monograph (Ref. (6)) and a more detailed list of references and bibliography is contained in Ref. (3).

VIKING PRESSURE VESSEL DESIGN

Consider now the Viking spacecraft shown in Figure 9. It is composed of two major subsystems: the Viking Orbiter (VO) and the Viking Lander Capsule (VLC). The Jet Propulsion Laboratory of Pasadena, California, is responsible for the design of the VO and the Martin Marietta Corporation of Denver, Colorado, is the prime contractor for the VLC.

Figure 9 shows the V-S/C in the cruise configuration. The VO fuel and oxidizer tanks are both cylindrical with hemispherical end closures. One of the two VO helium pressurization tanks can be seen in Figure 9. The two nitrogen tanks on the VO are not shown, but are located at the same level as the temperature control louvers. The VLC has four fuel tanks. Two are attached to the aeroshell and two are attached to the lander body.

Figure 10 is a tabulation of preliminary estimates of some of the important physical characteristics of the spacecraft pressure vessels. The pressure vessels are all constructed of titanium 6Al-4V. All four of the VLC pressure vessels are spherical and contain hydrazine with nitrogen as the pressurization medium. The VLC deorbit and reaction control system (RCS) tanks have bladders, weigh 10.7 pounds each, and have an anticipated maximum operating pressure of 375 psi. The VLC terminal descent engine fuel tanks do not have bladders and operate at 535 psi. The maximum operating pressure of the VO fuel (MMH) and oxidizer (N_2O_4) tanks is 300 psi; however, prior to launch they will be pressurized to only about 100 psi. They will not be brought to full pressure until after launch. The VO helium and nitrogen tanks both operate at 4000 psi. The weights given are, of course, only preliminary design values.

In the past, very few if any spacecraft pressure vessels have been designed on the basis of fracture mechanics data obtained specifically for that purpose. Rather, it has been utilized after the tank has been designed to provide quality assurance and to predict tank life and safety tolerances. For the Viking spacecraft, the required data will be obtained and used as the basis for design in addition to conventional design methods for tensile yielding. JPL will make use of previously obtained fracture mechanics data acquired on the Lunar Orbiter, Apollo, and Mariner programs. In addition, JPL will do testing of welded coupons and at temperatures not covered by previous testing. MMC, however, must obtain all new data because adequate data obtained in the presence of the fluid their tanks contain are not available. In both cases, the surface crack-type specimen will be used as most nearly simulating pressure vessel flaws of interest. Specimens such as shown in Figure 11 will be machined from forged titanium alloy of the type to be used in the pressure vessels. The test media will be the fluid that the tank will contain. Since the proof testing will be conducted at room temperature (in air) and at cryogenic temperatures (liquid nitrogen), these conditions must also be included for K_{Ic} tests. All tests will be uniaxially loaded in tension. Actual measured biaxial fracture toughness properties have been higher than uniaxial, therefore some degree of design safety may be realized by using uniaxial test data.

Fracture toughness values will be investigated for the four flaw conditions shown in Figure 11. MMC will test approximately 225 coupons in the process of establishing reliable values of the material fracture toughness (K_{Ic}) and the threshold stress intensity (K_{TH}). This will include 75 coupons for parent metal, 75 coupons for welds, and 75 for heat-affected zones. JPL will use approximately 150 in their program to obtain additional data. The data obtained in these programs will be analyzed statistically to determine values of K_{Ic} and K_{TH} that have a 99% probability of nonexceedance with a 95% confidence level. This is the same requirement set for MIL HDBK 5 "A" values.

Fracture toughness properties of forgings may vary with different lots and vendors; consequently, specimens will be tested from forgings supplied by several vendors. Finally, after the actual tank forgings have been received, specimens will be machined from excess material on the forging and tested to demonstrate conformance to the design values of K_{Ic} and K_{TH}.

As stated earlier, the concept of the proof test is the most important single factor in the use of fracture mechanics for pressure vessel design. Once the values of K_{Ic} and K_{TH} have been established, the relation between the operating stress (design stress) and the proof-stress levels may be determined. Formal agreement between JPL, MMC, and VPO has been arrived at on establishment of this relation and it has been incorporated in the Viking '75 Project Spacecraft Structural Design Criteria. The relation is shown on Figure 12. The proof test, if successful, establishes the fact that if a flaw exists in the tank it can be no larger than a given size. Hence the operating stress must be less than the proof stress by the factor K_{TH}/K_{Ic}. Since the proof test will be made at cryogenic temperatures, the variation of K_{Ic} with temperature must be accounted for by introducing the ratio of K_{Ic} at room temperature to K_{Ic} at proof temperature. Finally, to provide additional conservatism, a safety tolerance, ST, has been introduced.

The safety tolerances to be used by Viking are 1.35 for hazardous conditions and 1.15 for nonhazardous conditions. An example of the nonhazardous condition is the VO fuel and oxidizer tanks which will not be fully pressurized until after launch and hence cannot endanger personnel. In the Apollo program, the safety tolerance used was 1.0. While high confidence is placed in the fracture mechanics approach, an additional degree of conservatism of 1.15 was agreed upon. The hazardous safety tolerance was arrived at by introducing a factor of 1.2 which has previously been used by JPL. Thus the safety tolerance of 1.35 is approximately equal to 1.2 times the safety tolerance of 1.15. The proof stress, by agreement of all parties in the Viking Project, will be a given percent of the yield stress.

Figure 13 illustrates how the proof-test procedures to be followed by Viking are used to assure high reliability of the tanks in service and at the same time provide the most efficient lightweight design. The value of K_{Ic} is presently only a lower bound estimate based on the best data available and, of course, may change when all data have been obtained. The best available data indicate that for the thickness of the VLC tanks, the value of K_{Ic} at cryogenic temperature will be nearly the same as at room temperature. At greater thickness the material generally becomes more brittle and less tough at cryogenic temperatures. On the other hand, the yield stress at low temperature is considerably increased. If the proof test were made at room temperature the proof stress would be 0.90 of the yield stress or 144 psi. A successful test would then screen all flaws larger than a_1. For testing at cryogenic temperatures, the proof stress would be 0.85 of the yield stress (at that temperature) or 204 psi. The cryoproof will then screen all flaws larger than a_2 which is even smaller than a_1. Admittedly, the chance of failure is greater for the cryoproof, however, it permits a higher operating stress and a lighter weight tank with no degradation in reliability or decrease in the guaranteed life of the tank.

As a result of using the fracture mechanics approach, some Viking tanks will exceed ETR conventional factor of safety on proof and burst while others fall below those requirements. Figure 14 summarizes this situation for the Viking pressure vessels indicated. Both the VLC, RCS tanks and the VO fuel and oxidizer tanks exceed proof-test requirements. The VLC, RCS tanks also exceed ETR burst requirements and the Viking Project does not feel that a conventional factor of safety of 2.0 would provide an adequate margin of safety for the long-duration Viking mission for these tanks. Since the VO fuel and oxidizer tanks will not be pressurized until after the launch, they also meet the present range safety requirement. As can be seen from Figure 14, the other three sets of tanks will not meet the present ETR conventional factor of safety requirements. Nevertheless, it is felt that the fracture mechanics design method provides the same safety tolerance on these tanks as on the tanks which do meet the ETR safety factor requirements. It should also be noted that substandard quality control, prior to the proof test of Viking pressure vessels, would cause a high rate of failures in the proof test. Poor quality control of tanks designed by conventional methods, however, could lead to the much less acceptable possibility of failures in the presence of personnel.

SUMMARY

The Viking Project has adopted the use of fracture mechanics for design of all pressure vessels on the Viking spacecraft as being more realistic than conventional design methods and because it can assure the long life under sustained pressure necessary for the trip to Mars. The fracture mechanics approach considers both tensile yielding and crack propagation modes of failure. It accounts for flaws in the tank wall that may not otherwise be detected. It accounts for flaw growth under sustained loading and cyclic loading in the environment the tank will encounter. The proof test yields positive information on the maximum flaw in a tank and screens out all tanks that could burst prematurely. It does not require destructive testing of any tank.

SYMBOLS

a - semiminor axis of the ellipse $x^2/c^2 + y^2/a^2 = 1$ or crack depth of the semielliptical surface flaw, $\sqrt{\text{in.}}$
K_I - plane-strain stress-intensity factor, ksi$\sqrt{\text{in.}}$
K_{Ic} - plane-strain critical stress-intensity factor or fracture toughness of the material, ksi $\sqrt{\text{in.}}$
K_{Ii} - plane-strain stress-intensity factor at initial conditions, ksi $\sqrt{\text{in.}}$
K_{TH} - plane-strain threshold stress-intensity level, ksi $\sqrt{\text{in.}}$
N - number of cycles
r - radial coordinate, in.
S - nominal stress level, ksi
ST - safety tolerance
S_o - maximum design operating stress, ksi
S_p - proof stress, ksi
S_y - yield stress, ksi
t - thickness of plate (specimen), in.
σ_y - local stress in y direction, ksi

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ALL STRUCTURES HAVE FLAWS

FLAW SIZE GROWS DUE TO:

CYCLIC LOADING
STRESS CORROSION

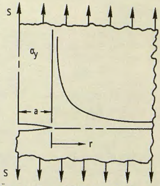
IN THE PAST TRADITIONAL DESIGN METHODS WORKED BECAUSE

DESIGN ALLOWABLES WERE LOW
MATERIALS WERE DUCTILE
TOLERANT OF FLAWS
INSENSITIVE TO ENVIRONMENT
FAILURE PLANE-STRESS

PRESENT DESIGN METHODS MUST ACCOUNT FOR

HIGH DESIGN ALLOWABLES
MATERIALS WHICH ARE BRITTLE
INTOLERANT OF FLAWS
MATERIALS ARE IN AGGRESSIVE ENVIRONMENT
FAILURE PLANE STRAIN

Figure 1.- Why fracture mechanics?



$\sigma_y = S + \frac{S\sqrt{\pi a}}{\sqrt{2\pi r}} + \ldots\ldots$

$K = S\sqrt{\pi a}$

CRACK BECOMES UNSTABLE WHEN

$K = S_f \sqrt{\pi a_c} \geq K_c$

Figure 2.- Relation between stress-intensity factor, K, and stress in the vicinity of a crack.

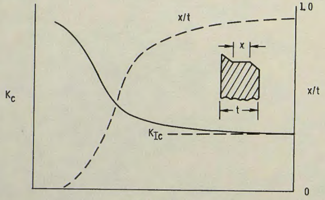


Figure 3.- Effect of plate thickness on fracture toughness and appearance of fracture.

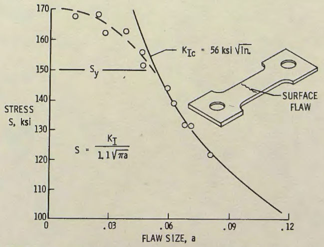


Figure 4.- Empirical flaw-size data, 6Al-4V STA titanium, room temperature.

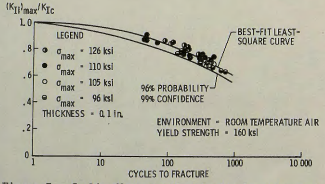
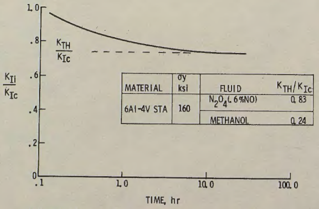


Figure 5.- Cyclic flaw-growth data for heat-treated 6Al-4V titanium.



MATERIAL	σy ksi	FLUID	K_{TH}/K_{Ic}
6Al-4V STA	160	N_2O_4(.6%NO)	0.83
		METHANOL	0.24

Figure 6.- Sustained-load flaw growth data.

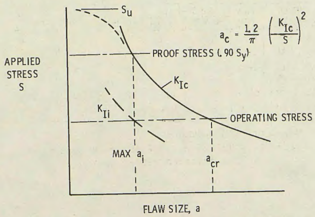


Figure 7.- Applied stress versus flaw size.

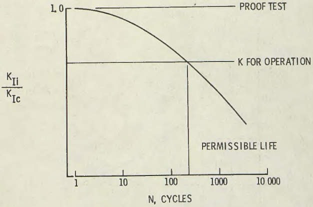


Figure 8.- Proof test as used to establish permissible life.

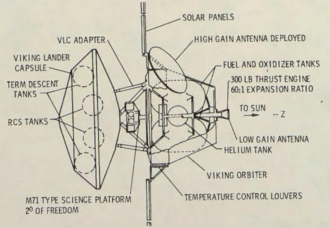


Figure 9.- Viking spacecraft in cruise configuration.

PRESSURE VESSEL	SIZE	NO.	SHAPE	FLUID	MAX PRESS.	MATERIAL	WT (LB)
VLC, RCS	22.14"ID	2	SPH.	N_2H_4/N_2	375 psi	Ti6Al-4V	29.9
VLC, TERM	20.93" D	2	SPH.	N_2H_4/N_2	535	Ti6Al-4V	20.8
VO, FUEL AND OXID.	55" X 36" D	2	CYL.	N_2O_4 or MMH	300	Ti6Al-4V	130.0
VO H_e TANK	22" D	2	SPH.	H_e	4000	Ti6Al-4V	120.0
VO N_2 TANK	12" D	2	SPH.	N_2	4000	Ti6Al-4V	30.0

Figure 10.- Viking spacecraft pressure vessel summary.

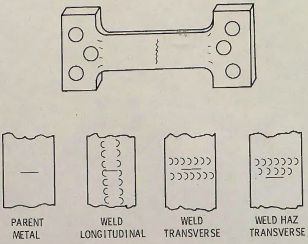


Figure 11.- Surface crack specimens.

$$S_0 = \left[\frac{K_{TH}}{K_{Ic,RT}}\right]\left[\frac{K_{Ic,RT}}{K_{Ic,PT}}\right]\frac{S_p}{ST}$$

WHERE:

S_0 = DESIGN STRESS

K_{TH} = THRESHOLD STRESS INTENSITY

$K_{Ic,RT}$ = CRITICAL STRESS INTENSITY AT ROOM TEMP.

$K_{Ic,PT}$ = CRITICAL STRESS INTENSITY AT PROOF TEST TEMP

S_p = PROOF TEST STRESS LEVEL

ST = SAFETY TOLERANCE

Figure 12.- Viking fracture mechanics criteria.

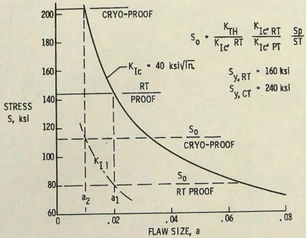


Figure 13.- Proof stress versus flaw size.

PRESSURE VESSEL	PROOF TEMP.	PROOF FACTOR		BURST FACTOR		WT. SAVED BY F. M.
		ETR REQ'D	ACTUAL	ETR REQ'D	ACTUAL	
VLC, RCS	R. T.	1.5	1.79	2.0	2.14	-1.4
VLC, TERM	CRYO	1.5	1.31	2.0	1.60	4.5
VO, FUEL AND OXID.	CRYO	1.5	1.70	2.0	2.0•	--
VO, H_e TANK	CRYO	1.5	1.35	2.0	1.54	20.0
VO, N_2 TANK	CRYO	1.5	1.35	2.0	1.54	5.0

• TANKS NOT FULLY PRESSURIZED ON PAD

Figure 14.- Influence of fracture mechanics on Viking pressure vessel design.