Rockwell International

(NASA-CR-120742) FRACTURE MECHANICS ANALYSIS OF A HIGH-PRESSURE HYDROGEN FACILITY COMPRESSOR Final Report (Rocketdyne) 34 p HC $3.75 CSCL 14D

N75-22784

Unclas
G3/38 19465

N75-22784

Rocketdyne Division
Rockwell International
6633 Canoga Avenue
Canoga Park, California 91304

RSS-8597

FINAL REPORT

FRACTURE MECHANICS ANALYSIS OF A HIGH-PRESSURE HYDROGEN FACILITY COMPRESSOR

11 October 1974

PREPARED BY

G. A. Vroman

G. A. Vroman
Project Engineer
Fracture Mechanics

APPROVED BY

J. L. Thompson
Director
Technical Specialties

FOREWORD

The work summarized in this report was performed under contract NAS8-27980, Space Shuttle Engine Program, Coca 4B Reactivation Review.

ABSTRACT

The investigation and analysis of a high-pressure hydrogen facility compressor is chronicled, and a life prediction based on fracture mechanics is presented. Crack growth rates in SA 105 Gr II steel are developed for the condition of sustained loading using a hypothesis of hydrogen embrittlement associated with plastic zone reverse yielding. The resultant formula is compared with test data obtained from laboratory specimens.

ACKNOWLEDGEMENT

The suggestions and critiques provided by Dr. P. Paris, consultant with Del Research Corporation, are gratefully acknowledged.

CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY CONCLUSIONS

The following conclusions have been reached as a result of the subject analysis:

1. The safe operating life at 15,000-psi hydrogen maximum operating pressure is in excess of 100 cycles.
2. The safe operating life at 10,000-psi hydrogen maximum operating pressure is in excess of 460 cycles.
3. The equivalent damage in terms of life cycles caused by partial excursions in pressure has been estimated.
4. Conditions hazardous to personnel exist at hydrogen pressures above 5000 psi during the first half of the safe operating life (before the first 230 cycles at 10,000 psi).
5. Conditions hazardous to personnel exist at all hydrogen pressures after the first half of the safe operating life (after the first 230 cycles at 10,000 psi).

BACKGROUND

In February of 1974, this office was requested to assess the feasibility of performing a fracture mechanics-based life prediction analysis of the high-pressure hydrogen facility compressor at Coca 4B test site. It was concluded that such an analysis could be performed to indicate qualitatively the criticality of the compressor for the intended service. Crack growth rate data (cyclic) were available for a material similar to the one from which the compressor was constructed, and the compressor structural details were largely known. The 4-inch-thick, welded, 23-inch-diameter, high-pressure spheres were selected to be the most critical components, and life prediction analyses were performed. In recognition that sustained-load flaw growth was not accounted for in the fracture data (cyclic), a life factor of 2 was used to reduce the nominal prediction. It was concluded that the compressor life was indeed critical and significantly less than the required service life.

The next several months were spent largely in a technical interchange with the customer. Most of the effort was spent in performing additional calculations and supplying background information, both at customer request. Also during this period, additional crack growth data were obtained for cycle periods of 1 and 10 seconds/cycle. The fracture specimens were cut from forgings of the same material as the subject pressure vessels, and the cyclic data confirmed the values used in previous analyses. At the end of this period, there was clearly a technical disagreement between this office and the customer regarding the criticality of the compressor. It was decided to obtain an independent assessment by Dr. P. Paris of Del Research Corporation, an internationally recognized consultant.

Dr. Paris was on-site at Canoga on 1 June. This morning was spent in briefings intended to provide Dr. Paris with all of the basic information available concerning the compressor system, the materials, and the hydrogen-environment fracture data. Dr. H. Marcus of the Rockwell International Science Center also contributed in the discussions. This office intentionally remained out of the briefings to ensure the integrity of Dr. Paris' independent assessment. The most significant event of the morning briefings was the presentation of sustained-load crack growth data (not previously shown) by Dr. W. Chandler. When Dr. Paris gave his preliminary assessment in the afternoon, he focused on the sustained-load data and suggested that failure might occur in as few as 10 cycles. In his documented report of 7 June, Dr. Paris expressed essentially the same opinion.

This office did not accept the above-mentioned sustained-load data at face value, and pursued an inquiry to determine the conditions of testing. It was found that all loadings which resulted in a significant amount of crack growth had been preceded by at least 1000 cycles of fatigue cycling (in hydrogen) at the same stress intensity level. This observation led to a new theory which seemed to explain the existing data and suggested a means of quantifying sustained-load crack growth for service conditions (where no fatigue cycling occurs between sustained loads).

Meetings were held on 12 and 13 June at the Brown University (Providence, Rhode Island) office of Dr. Paris to review the sustained-load data and to discuss other aspects of the life prediction analyses. At the conclusion of these meetings, Dr. Paris was largely in agreement with this office, and he documented his new position with an addendum to his previous report. By mutual agreement, it was recommended that additional growth rate data be obtained at loading periods of 100 and 1000 seconds/cycle.

BASIC ASSUMPTIONS

The following assumptions form the basis for fracture mechanics life prediction of the hydrogen compressor system:

1. The most critical system component is the 23-inch-diameter, 4-inch-thick, welded, high-pressure (15,000-psi) hydrogen sphere.
2. The most critical and likely location of an undetected crack for a welded sphere is in the weld bead, on the inner surface (exposed to hydrogen), and oriented normal to the weld pass direction.
3. The crack shape aspect ratio is 1/2, i.e., the surface length (major diameter of a semi-ellipse) is twice the crack depth.
4. The high fracture toughness of the subject material precludes the use of proof test logic for determining the maximum flaw size after proof test.
5. The maximum probable flaw depth after proof test (initial flaw size in service) is 1.00 inch.
6. The weld material stress, normal to the crack, during proof loading is 0.80 times the material ultimate tensile strength. This stress represents a combined effect of welding residual stresses, applied proof stresses, and weld material yielding.
7. The weld material stress, normal to the crack, during operation is linearly proportional to the ratio of the operating pressure divided by the proof pressure.
8. The "Irwin" part-through crack equation adequately predicts the applied stress intensity for crack depths up to and including one-half the wall thickness. Stress intensity values for deeper cracks are unpredictable.
9. The sustained-load crack growth due to hydrogen-embrittlement effects is one-tenth of the plastic zone size calculated from the maximum load reached during the cycle.

10. The mechanical fatigue component of the total growth per cycle is small relative to the hydrogen-embrittlement effect.

11. The above assumptions are sufficiently conservative to preclude the necessity for additional safety factors in life prediction calculations.

CRACK GROWTH RATES

During the course of the subject investigation considerable effort was required to establish the crack growth rates that would occur during service operating conditions. Real-time sustained-load holding periods of 6 hours or more precluded the gathering of very much laboratory data under service conditions. However, an analysis of available data obtained at much smaller loading times (5 minutes/cycle and 1 hour/cycle) suggested a hydrogen-embrittlement fracture mechanism that could be proven (or disproven) with relative ease in the laboratory, using load holding times of 100 seconds/cycle and 1000 seconds/cycle. It was recognized from smooth bar fatigue test results that hydrogen-embrittlement effects were directly related to plastic flow in the material. Extending this knowledge to material conditions near the crack front, the following fracture mechanism was postulated:

1. Hydrogen diffusion is largely determined by plastic strain.
2. Sustained-load growth occurs where hydrogen is diffused.
3. Crack growth arrest occurs where hydrogen is not diffused.
4. After many cycles in fatigue, hydrogen is throughout plastic zone.
    a. Sustained load grows crack through plastic zone.
    b. Crack arrest occurs at end of plastic zone.
5. Without fatigue cycles, hydrogen diffuses only a small depth.
    a. Depth assumed same as material seeing full hysteresis loop.
    b. Crack growth per cycle equals hydrogen depth.
6. Hydrogen diffusion is also time-dependent.

Dr. E. F. Cain recognized that if hydrogen was not present during plastic material strain, then embrittlement should not occur. Tests using a helium environment during loading and unloading (during plastic straining), but also subjecting the specimen to high-pressure hydrogen during the load-holding period (no plastic strain), resulted in no measurable crack growth. Although not conclusive, the helium-hydrogen testing tended to confirm the postulated fracture mechanism.

An attempt to quantify item 5a above was based on theoretical estimates of reversed yielding (during unloading) near the crack front. Estimates ranged from one-tenth to one-quarter of the tension plastic zone size. It was reasoned that material which did not undergo reversed yielding would have much less plastic strain through the cyclic hysteresis loop, much less hydrogen diffused through the material, and much less crack growth under sustained load. It will be shown in the following pages that the assumption of a one-tenth plastic zone size growth per cycle is conservative for this material in a 15,000-psi hydrogen environment.

At this time, a complete report of material testing is not available for reference so a summary of the pertinent data is presented in Table 1. Two stress intensity ranges, 20 and 40 ksi $\sqrt{\text{inch}}$, were selected on the basis of previously obtained cyclic data and specimen limitations. The primary variable was the sustained-load hold time, with the end objective of determining crack growth during a 6-hour duration. It can be seen in the test results that hold time did not have a significant effect at the lower stress intensity. A trend did exist at 40 ksi $\sqrt{\text{inch}}$, but it was not sufficiently definitive to be used for crack growth prediction. As expected, the time-dependent growth rate (μin./sec) was significantly reduced as the cycle period was extended. The incremental change between the 10-sec/cycle growth and the 100-sec/cycle growth was 1.22 μin./sec, whereas the time rate of growth between 100 sec/cycle and 1000 sec/cycle was 0.27 μin./sec (taking the data at face value). These numbers support the hypothesis that the growth/cycle approaches an asymptote as the cycle period becomes very large. However, the meager amount of data precludes calculation of the asymptote value. The assumed crack growth based on plastic zone size is more than three times any of the measured values, so it is believed that the time-dependent factor has been adequately accounted for.

Also shown in Table 1 are two data values for ramp loading times of 100 seconds. It was noted that the hydrogen compressor system required periods on this order to reach maximum pressure, whereas the other data were acquired using a ramp rate of 0.5 second. On the theory that plastic strain (and therefore hydrogen diffusion) occurs during loading and unloading, it was expected that the ramp rate could greatly

TABLE 1. CRACK GROWTH RATE DATA SUMMARY

SA 105 STEEL IN 15,000-PSI HYDROGEN

ΔK, ksi $\sqrt{\text{inch}}$	R	Ramp Time, seconds	Hold Time, seconds	DADN, μin./cycle
20	0.1	0.5	9	120
↓	↓	↓	9	220
			99	81
			999	200
20	0.1	100	100	132
40	0.1	0.5	9	440
↓	↓	↓	9	480
			99	570
			999	810
40	0.1	100	100	790

influence the resulting sustained-load growth rate. The data show that, at a 40-ksi $\sqrt{\text{inch}}$ stress-intensity range, the effect is significant but not overwhelming. These data are included in the comparison with the assumed growth rate discussed below.

Figure 1 shows a plot of the data from Table 1 along with the assumed crack growth rate of one-tenth the plastic zone size (based on 58.0 ksi material yield strength). The dashed line that seems to fit the test data was obtained by dividing the assumed growth rate by a factor of 4, hence the similarity in curve shapes. The uppermost data point at 20 ksi $\sqrt{\text{inch}}$ is about one-third of the assumed rate, and at 40 ksi $\sqrt{\text{inch}}$ the ratio is even better. It is assumed therefore that the assumed growth rate is adequately conservative.

In all of the above discussions the crack growth rates have been related to the parameter of stress intensity, always on the basis of 15,000-psi hydrogen pressure.

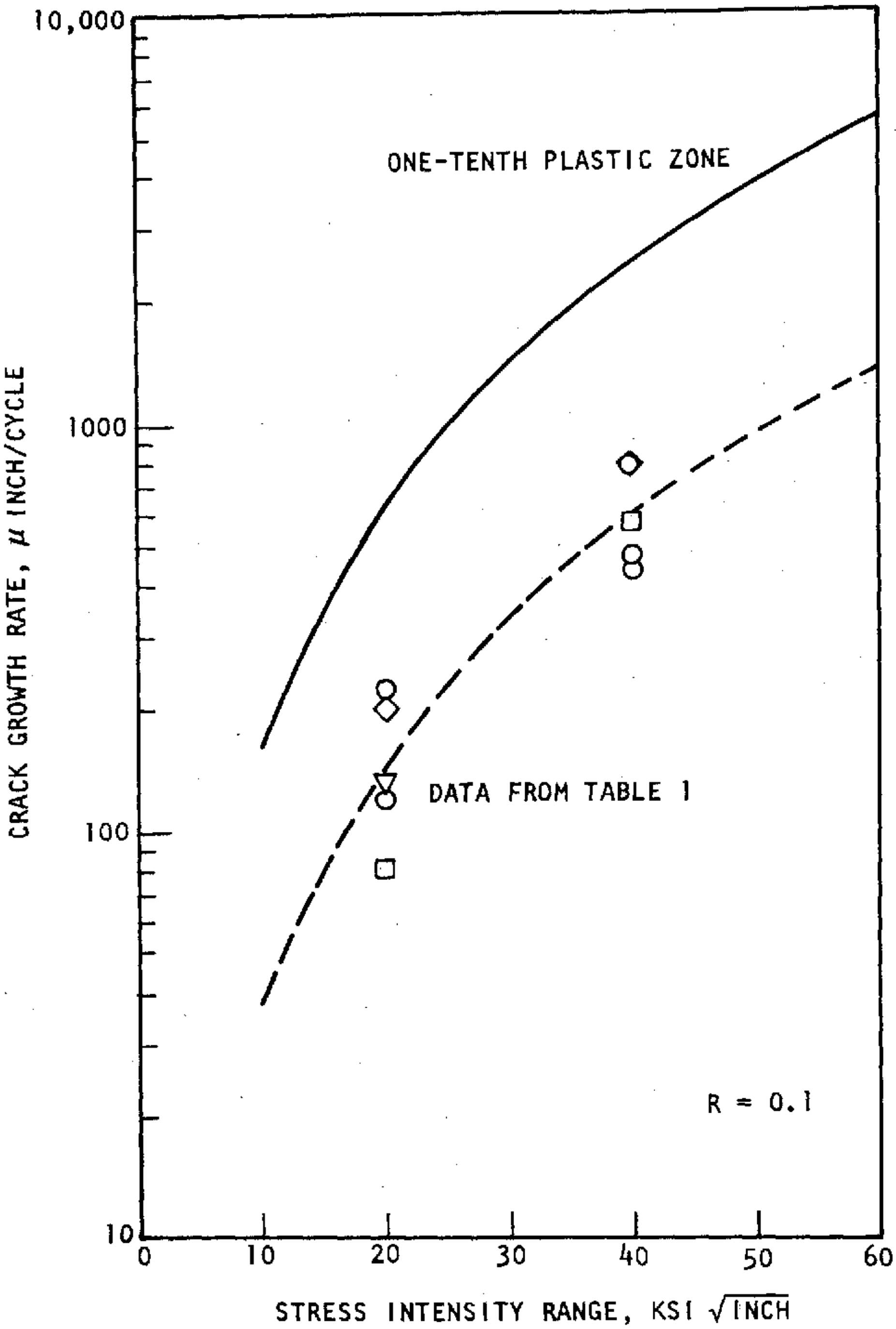

Figure 1. Comparison of Assumed Growth Rate With Test Data

Obviously, in a pressure vessel the stress intensity must be a reflection of the hydrogen pressure. Therefore, a given crack size will have a high hydrogen pressure associated with a high stress intensity and a low hydrogen pressure associated with a low stress intensity. The practical limits of this investigation prevent a full study of the pressure effect on growth rate so the analysis must be based on the worst condition, i.e., the 15,000-psi hydrogen environment. It is believed that these growth rates introduce an additional conservatism in the analytical life predictions for pressures less than 15,000 psi.

CYCLE LIFE FOR 10,000-PSI PRESSURE

After reviewing the structural characteristics of the various components of the hydrogen compressor system, it seemed evident that the second-stage discharge pulse quieter spheres were significantly more critical than any of the other components. Therefore, the compressor system life is determined by the life of these spheres. The two major factors that determine the spheres to be critical are: (1) the 4-inch-thick welds that are very likely to contain crack-like defects, and (2) the virtual impossibility of adequately inspecting the welded joint to detect defects. The relatively low strength and high fracture toughness of the material could allow an improbably large crack to survive proof test without detection, so a judgment probability estimate was used rather than proof test logic in determining the maximum possible flaw size. Also, consideration was given to the size of the weld heat-affected zone in estimating the crack shape. The fracture mechanics calculations below are based on an initial flaw that is semi-circular in shape, oriented normal to the direction of the weld pass, 1.00 inch deep, and exposed to the vessel's internal hydrogen pressure. The basic information listed below provides a brief structural description of the second-stage discharge pulse quieter spheres:

Sphere Diameter: 23.1 inches OD

Wall Thickness: 4.3 inches

Construction: Forged Hemispheres Welded

Material: ASME SA 105 Gr II Steel

F_{ty} = 58.0 ksi, F_{tu} = 79.4 ksi

Proof Pressure: 26,250 psi

Design Operating Pressure: 15,000 psi

The Irwin stress intensity equation for part-through cracks is used as a basis for fracture mechanics calculations. This is a relatively crude approximation for stress intensity because it does not account for the compound curvature of the pressure vessel walls but rather assumes the crack to be in a flat plate. Also, the equation needs an additional correction factor when the crack depth exceeds half the plate thickness, but because of the compound curvature this will not be attempted. Hopefully, the conservatism of stopping crack growth analysis at half the wall thickness (2.1-inch crack depth) will offset the unconservatisms inherent in applying a flat plate equation to a compound-curvature problem.

The weld nugget solidifies at a time when large thermal gradients exist across the weld joint. As the joint cools after welding, the thermal gradients vanish and are reflected as strain gradients, thereby causing high residual tensile stress in the weld region. The process is, in fact, a casting process and as in castings it is not unusual to create shrink cracks when the stress/strain level becomes too high. Assuming that this type of defect exists in the spheres, then it follows that the residual stress (in the direction of welding) is on the order of the material yield strength. Adding the proof pressurization stress to the residual stress must cause a significant amount of plastic strain, with the stress level approaching the material ultimate strength. For this analysis it is assumed that the weld region stress at proof pressure is 80 percent of the material ultimate strength.

$$\sigma_{proof} = 0.80 \times 79.4 = 63.5 \text{ ksi}$$

For all pressurizations in service the stresses will be lower and linearly proportional.

$$\sigma_{operating} = \sigma_{proof} \left(p_{operating}/p_{proof}\right)$$

For 10,000-psi operating pressure:

$$\sigma_{10,000} = 63.5 \ (10,000/26,250) = 24.2 \text{ ksi}$$

Conservatively calculating the plastic zone size on the basis of a high ratio of σ/σ_{ys}:

$$r_y = \frac{1}{6\pi} \left(\frac{K}{\sigma_{ys}}\right)^2$$

where

K = stress intensity

σ_{ys} = material yield strength

$$K = 1.12\ \sigma\sqrt{\pi a/Q} = 1.32\ \sigma\sqrt{a}$$

$$(a/2c = 0.5,\ \sigma/\sigma_{ys} = 1.0)$$

$$K_{operating} = 1.32 \times 24.2\sqrt{a} = 31.9\sqrt{a}$$

$$r_{y\,operating} = \frac{1}{6\pi}\left(\frac{31.9\sqrt{a}}{58.0}\right)^2 = 0.0161a$$

$$\text{DADN} = \text{crack growth rate} = r_y/10 = 0.00161a$$

Table 2 uses the above result to arrive at the number of cycles required to grow an initial crack 1.00 inch deep to the half wall thickness depth of 2.10 inches, assuming a constant crack growth rate over each 0.10-inch increment. Rounding the resultant value to two significant figures arrives at a predicted life of 460 cycles for the critical component of the hydrogen compressor system.

TABLE 2. SECOND-STAGE DISCHARGE PULSE QUIETER
CYCLE LIFE FOR 10,000-PSI MAXIMUM PRESSURE

a_{avg}	DADN $= \frac{r_y}{10}$	$\Delta N = \frac{\Delta a}{\text{DADN}}$
1.05	0.00169	59.2
1.15	0.00185	54.0
1.25	0.00201	49.7
1.35	0.00217	46.0
1.45	0.00233	42.9
1.55	0.00249	40.1
1.65	0.00265	37.7
1.75	0.00282	35.5
1.85	0.00298	33.6
1.95	0.00314	31.9
2.05	0.00330	30.3
		$\sum\Delta N = 461$

ACCUMULATED DAMAGE CALCULATION

FOR

HIGH-PRESSURE HYDROGEN SERVICE

The procedure described below is intended to be used for calculating the damage accumulation caused by service operation of the high-pressure hydrogen compressor at SSFL. The actual service operation of the compressor will not always be to the same maximum pressure. Also, the pressure excursion will not always be a simple variation from zero to maximum to zero. A cyclic damage equivalence calculation is necessary to have an accounting procedure for limiting the pressurization in service. The 10,000-psi hydrogen maximum operating pressure has been used as a reference basis, and all damage calculations are expressed as equivalent 10,000-psi cycles. The operating life is limited to 460 equivalent 10,000-psi cycles.

Step 1. Divide the pressure-time history of the compressor system into a series of block loadings.

Each pressurization, from zero to one or more pressures to zero, constitutes one block of loading. The damage accumulation caused by each block of loading is determined by the pressure excursions that occur within the block. Figure 2 illustrates the division of an example pressure-time history into loading blocks. Note that the number of loading blocks is established by the number of times that the pressure returns to zero, and is independent of the higher pressure excursions.

Step 2. Divide each block loading into a set of pressure excursion cycles which may be superimposed to reconstruct the block loading. Disregard holding times and pressure variations of 5 percent or less as pressure excursions. Pressure excursions from P_a to P_b to P_a are equivalent to pressure excursions from P_b to P_a to P_b.

Figure 3(a) illustrates equalities to be used in defining pressure excursions. Note that when the hold times and the order of pressure levels are disregarded, the pressure excursions of 3(a) are equal for the purpose of damage calculations.

Figure 3(b) applies the results of Figure 3(a) and the principle of superposition to divide the given loading block into two pressure excursion cycles. Figure 3(c) further illustrates the same principles.

Referring back to Fig. 2, it can be seen that block 1 consists of one pressure excursion cycle from 0 to P_3 to 0. Block 2 consists of one pressure excursion cycle from 0 to P_1 to 0. Block 3 consists of two pressure excursion cycles: 0 to P_3 to 0, and P_3 to P_2 to P_3.

Step 3. Calculate the equivalent cyclic damage caused by each pressure cycle excursion using the following formula:

$$N \text{ equivalent cycles} = P_{max} (P_{max} - P_{min})^2 \times 10^{-3}$$

where: P_{max} = *ksi, maximum hydrogen pressure during the excursion*
P_{min} = *ksi, minimum hydrogen pressure during the excursion*

Figure 4 provides example pressure cycle excursions that can be used to demonstrate the procedure of Step 3. The N equivalent cycles of excursion cycle A are calculated below:

$P_{max} = 5,\ P_{min} = 0$
$N = 5 \times (5 - 0)^2 \times 10^{-3} = 0.125$

The equivalent cyclic damage of all the pressure excursion cycles of Fig. 3 are listed in the summary comprising Table 3.

Step 4. Sum the equivalent cyclic damage caused by all of the loading blocks and the pressure excursion cycles within the loading blocks.

Figure 5 provides an example of three loading blocks to illustrate the procedure of Step 4. The pressure excursion cycles were chosen to correspond with those of Fig. 4. Table 4 shows the summary calculations leading to the total number of equivalent damage cycles caused by the three loading blocks.

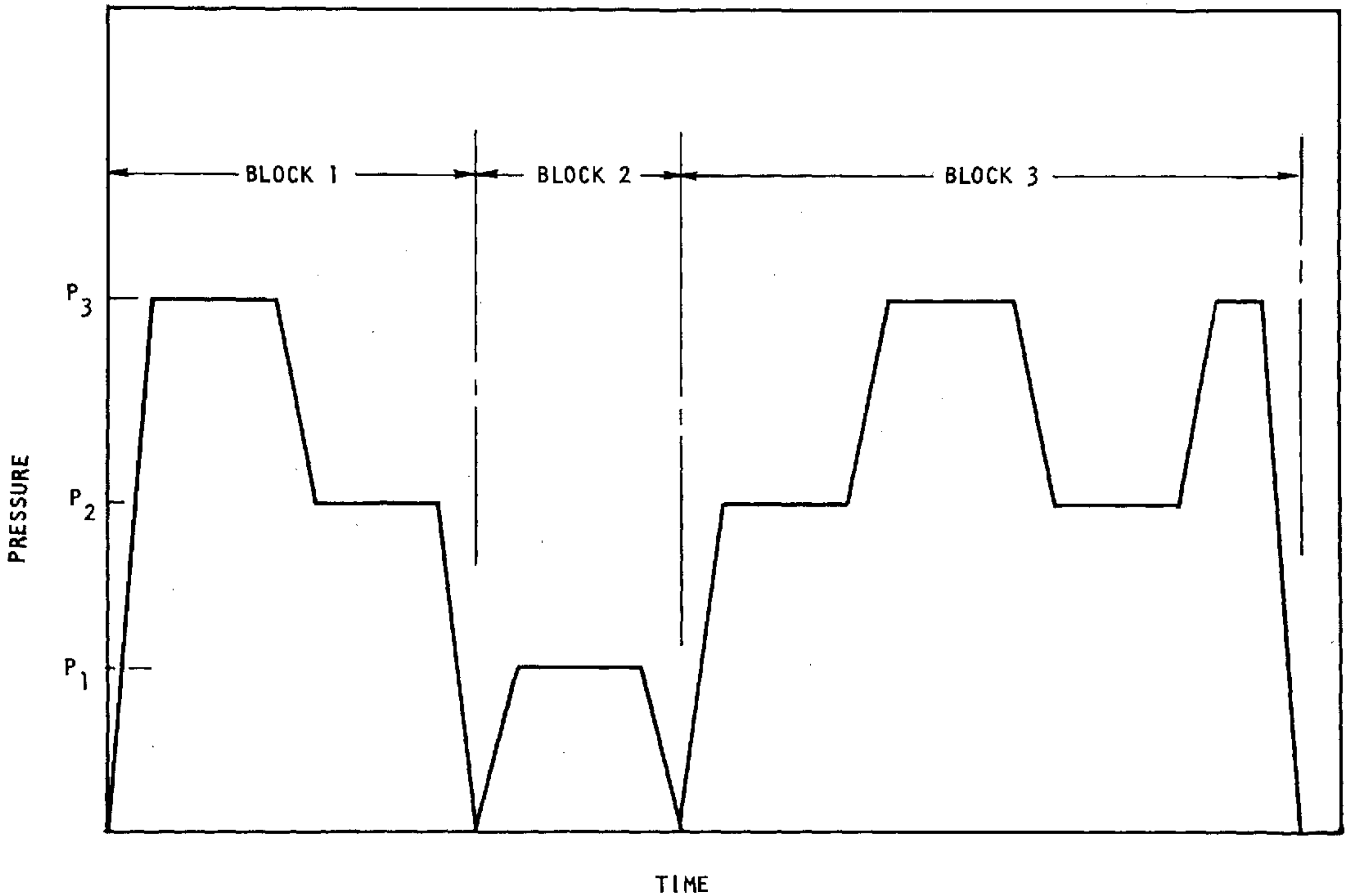

Figure 2. Pressure Loading Blocks

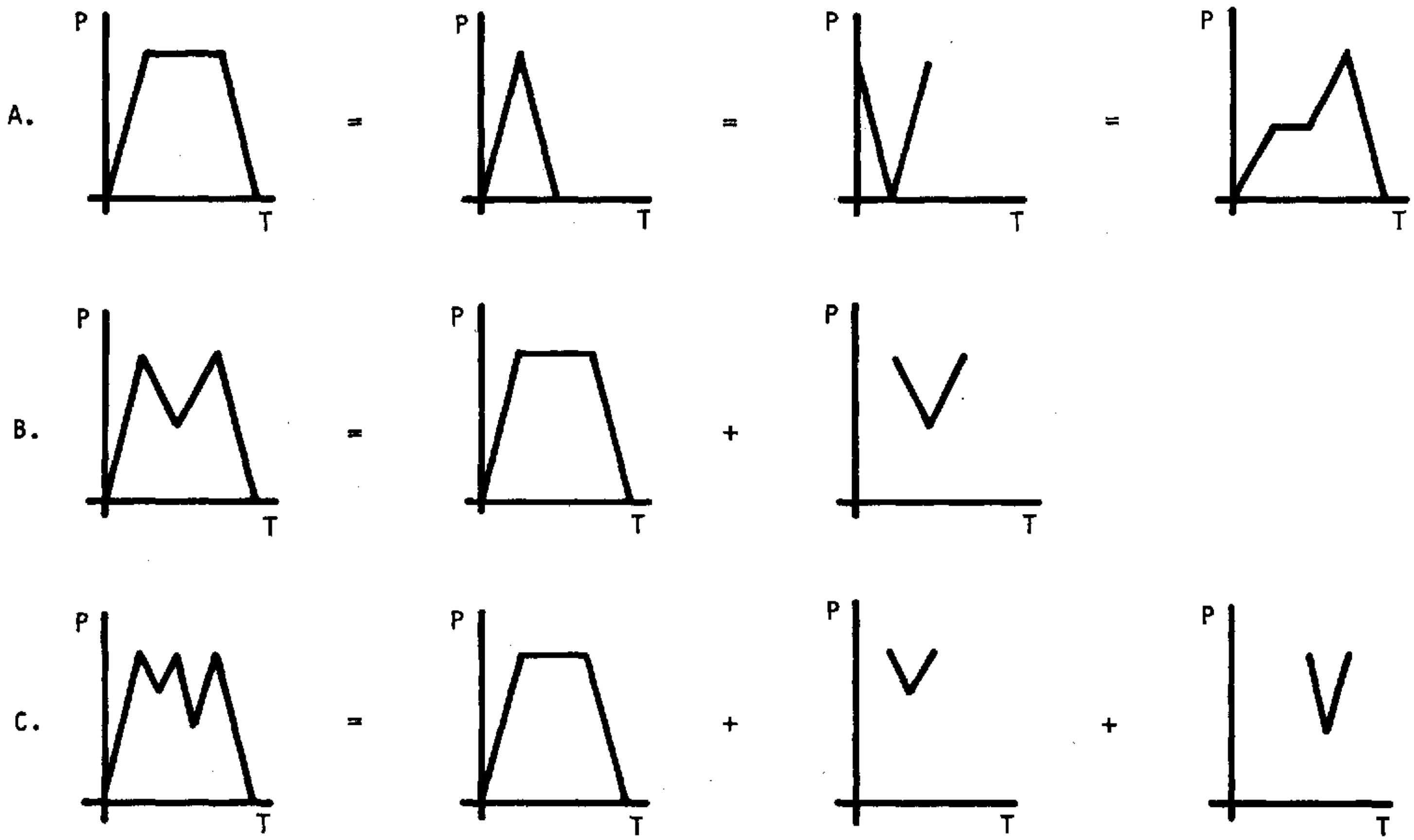

Figure 3. Pressure Excursion Cycles

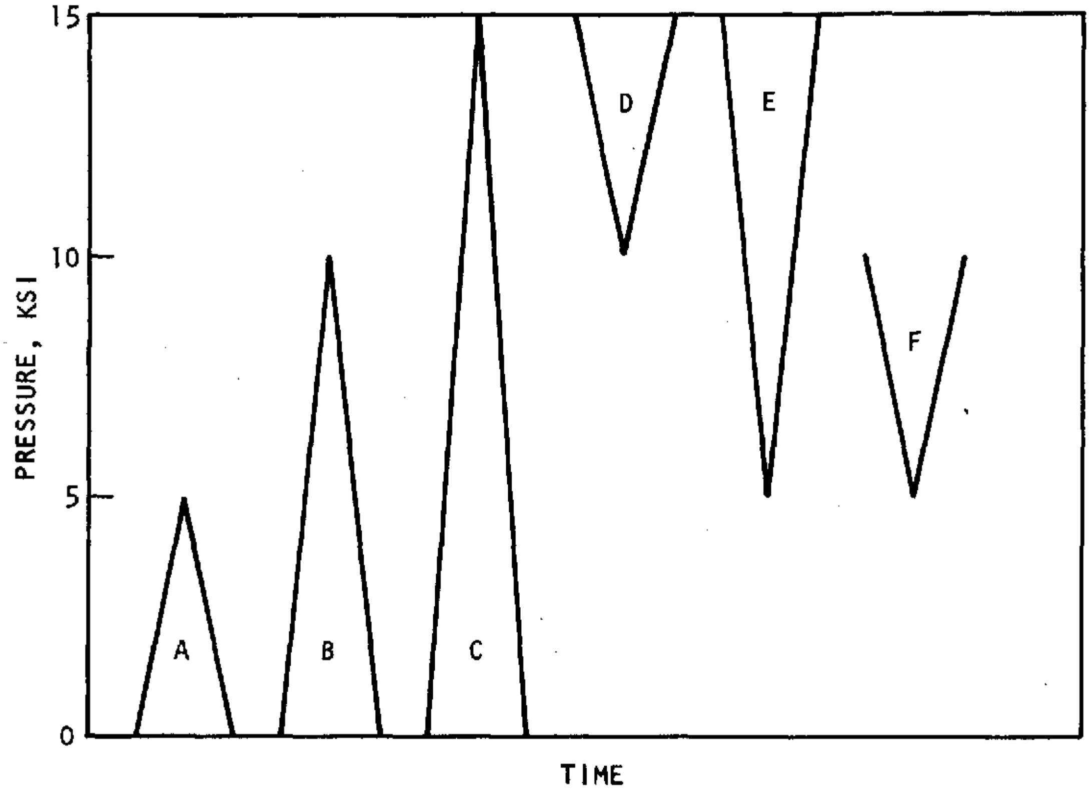

Figure 4. Example Pressure Cycle Excursions for Damage Calculation

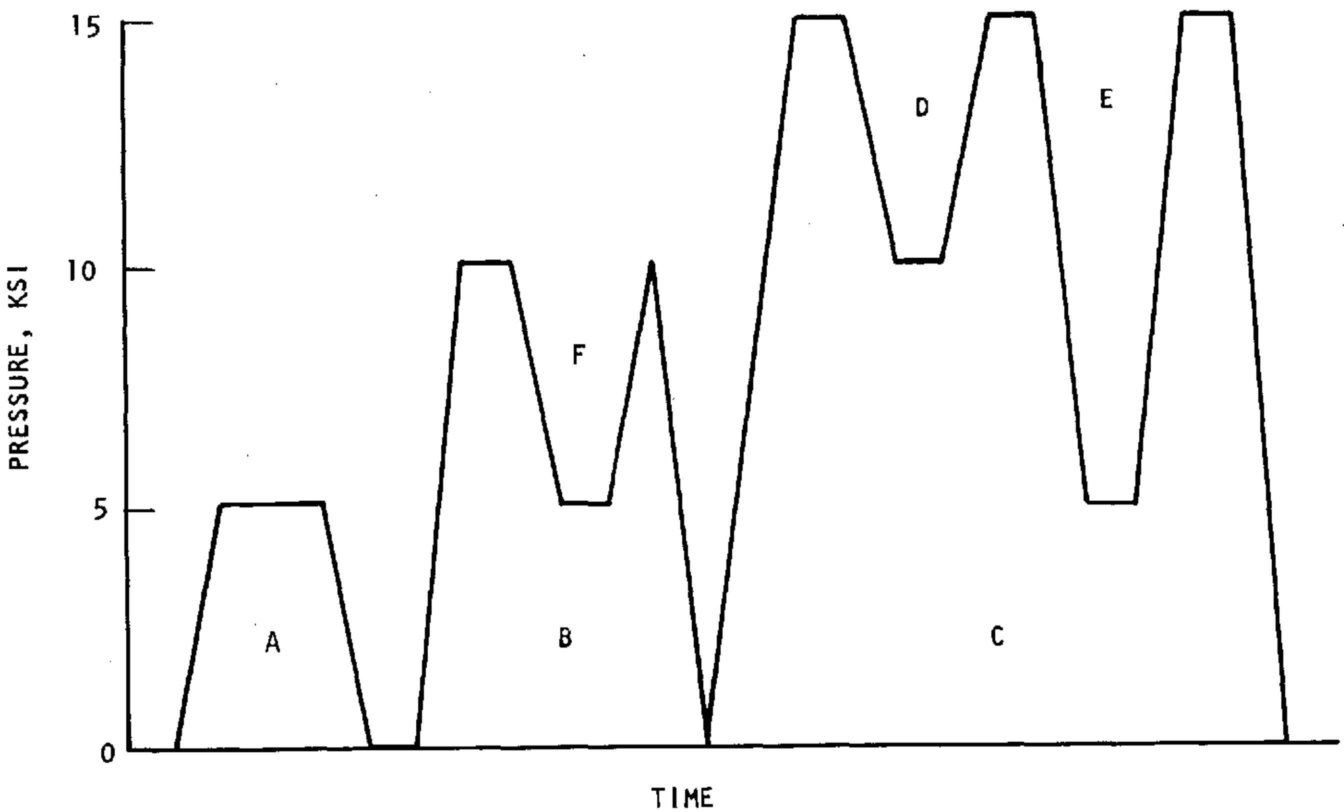

Figure 5. Three Loading Blocks for Example of Damage Calculation

TABLE 3. EQUIVALENT CYCLIC DAMAGE OF EXAMPLES SHOWN IN FIG. 4

Excursion Cycle	P_{max}	P_{min}	N
A	5	0	0.125
B	10	0	1.000
C	15	0	3.375
D	15	10	0.375
E	15	5	1.500
F	10	5	0.250

TABLE 4. EQUIVALENT CYCLIC DAMAGE OF LOADING BLOCKS SHOWN IN FIG. 5

Block	Cycle	P_{max}	P_{min}	N
1	A	5	0	0.125
2	B	10	0	1.000
	F	10	5	0.250
3	C	15	0	3.375
	D	15	10	0.375
	E	15	5	1.500
Total Equivalent Damage Cycles = 6.625				

DESIGN LIFE

The design life requirement for the total program is estimated to be as many as 2000 operating cycles. An exact number is not required because there is little doubt that a material change is required as soon as possible for the critical compressor parts. The new material is apparently not embrittled by hydrogen, and the service life will not be limited after the change is made. However, testing requirements demand that a number of pressurizations be performed during the interim.

The design life requirement for the part of the program prior to compressor rework (materials change) has not been established. Verbal information indicates that adequate life is available to support planned testing.

HAZARD TO PERSONNEL

Failure of a high-pressure hydrogen sphere will most likely result in high-velocity steel fragments permeating a large surrounding region. Obviously, great care must be taken to have no personnel present when this might occur. Fracture mechanics technology has provided valuable information regarding the hazardous conditions leading to failure.

When a compressor system is never operated above 5000-psi hydrogen pressure, there is little likelihood that an initial crack has grown significantly during service operation. Therefore, there is a relatively small hazard when personnel are present.

When a compressor system has been operated above 5000-psi hydrogen pressure (10,000 psi or 15,000 psi), there is a strong possibility that significant damage (increase in crack size) was caused by the higher pressures. This negates the rationale for concluding that operation at 5000 psi or less is always safe. Also, it should be noted that failure on a succeeding cycle may occur at a much lower level than previously sustained. This has been proven by both fracture analysis and testing. The degree of hazard for 5000-psi operation is determined by how much damage was caused by the higher pressures; the more high-pressure cycles, the greater degree of hazard. It is recommended that the compressor not be operated (at any pressure) with personnel present after half of the fracture mechanics predicted life has occurred in service.

APPENDIX A

COMPUTER PROGRAM FOR CALCULATING EQUIVALENT DAMAGE

A computer program has been devised which automatically converts input data of real-time pressure history into equivalent numbers of 10,000-psi cycles, adding the incremental damage to the number of accumulated cycles at the data start point. The computer program thereby provides the total accumulated damage in terms that can be compared to equivalent 10,000-psi cycle life limitations.

In addition to applying the criteria that defines "loading blocks" and "pressure excursion cycles," the computer program utilizes the technique of range pairing to reconstruct each loading block in terms of equivalent pressure excursion cycles. A listing of the computer program is shown in Fig. A-1(a) and A-1(b).

The following information constitutes instructions for use on a General Electric Computer terminal.

As input, the H-440 FORTRAN program requests the following:

1. Compressor ID (from 1 to 6 characters)
2. Accumulated cyclic damage (prior)
3. Run ID (from 1 to 6 characters)
4. Data (enter pressures (psi) for run)

Repeat Steps 3 and 4 for a maximum of 500 pressures. To terminate input, press carrier return key when program requests run ID.

The program produces the following output:

1. Equivalent cyclic damage for each cycle
2. Incremental cyclic damage (Σ1.)
3. Prior cyclic damage (Input 2.)
4. Accumulated cyclic damage (Σ2. and 3.)

Figure A-2 shows an example pressure history used to test the various program functions. Figure A-3 shows the output obtained when the example was input.

```
$NDM
C      DAMAGE CALCULATIØN - HIGH PRESSURE HYDRØGEN SERVICE
C      FØR G. A. VRØMAN  BY  J. R. WHITNEY  AUGUST 1974
C
       DIMENSIØN D(6,500),P(50)
       DATA ND/500/,NP/50/,B/"      "/
C
     5 PRINT,"ENTER CØMPRESSØR ID"
       READ 10,C
    10 FØRMAT(A6)
       PRINT 15,C
    15 FØRMAT(" ENTER ACCUMULATED CYCLIC DAMAGE FØR CØMPRESSØR ",A6)
       READ,TNE
       SNE=0
       N=1
    20 NN=N
       PRINT,"RUN ID?"
       READ 10,D(1,N)
       IF(D(1,N) .EQ. B) GØ TØ 300
       DØ 30 I=1,NP
    30 P(I)=-999.
       PRINT,"DATA?"
       READ,P
       DØ 40 MM=1,NP
       IF(P(MM) .EQ. -999.) GØ TØ 50
    40 CØNTINUE
       MM=NP+1
    50 MM=MM-1
       IF(P(MM) .EQ. 0.) GØ TØ 50
       MM=MM+1
       P(MM)=0
       M1=2
       BN=1.
   100 DØ 110 M=M1,MM
       IF(P(M) .EQ. 0.) GØ TØ 120
   110 CØNTINUE
       M=MM+1
   120 IF(M .NE. MM) M=M-1
       I1=M1-1
       I=I1
   200 I=I+1
   210 IF(I .GE. M) GØ TØ 230
       T=(P(I+1)-P(I))/(P(I)-P(I-1))
       IF(T .LT. 0.) GØ TØ 200
       DØ 220 J=I,MM
   220 P(J)=P(J+1)
       MM=MM-1
       M=M-1
       GØ TØ 210
   230 K=0
       IF(M .EQ. MM) M=M-1
       DØ 240 I=M1,M
```

Figure A-1(a). Computer Listing of Accumulated Damage Calculation Program

```
      IF(P(I) .GE. P(I-1)) GØ TØ 240
      T=P(I)
      P(I)=P(I-1)
      P(I-1)=T
      K=1
  240 CØNTINUE
      IF(K .EQ. 1) GØ TØ 230
      CN=0.
      M2=(I1+M)/2
      IF(C .EQ. B) PRINT11,I1,M,(P(I),I=I1,M)
   11 FØRMAT(2I4/(8F8.0))
      IMAX=M
      DØ 250 I=I1,M2
      IF(P(I) .EQ. P(IMAX)) GØ TØ 250
      CN=CN+1.
      D(1,N+1)=D(1,N)
      D(2,N)=BN
      D(3,N)=CN
      D(4,N)=P(IMAX)
      D(5,N)=P(I)
      D(6,N)=P(IMAX)*(P(IMAX)-P(I))**2*1.E-12
      SNE=SNE+D(6,N)
      N=N+1
  250 IMAX=IMAX-1
      BN=BN+1.
      IF(M+1 .EQ. MM) GØ TØ 20
      M1=M+2
      GØ TØ 100
C
  300 PRINT 310,C
  310 FØRMAT(/////" DAMAGE CALCULATIØN FØR CØMPRESSØR ",A6//
&     " RUN      BLK  CYC     PMAX     PMIN     NE")
      N=N-1
      DØ 320 J=1,N
      PRINT 330,(D(I,J),I=1,6)
      IF(D(1,J) .NE. D(1,J+1)) PRINT,
  320 CØNTINUE
  330 FØRMAT(1X,A6,2F5.0,2F8.0,F9.3)
      ANE=TNE+SNE
      PRINT 340,SNE,TNE,ANE
  340 FØRMAT(/8X,"INCREMENTAL CYCLIC DAMAGE",F9.3
&     //14X,"PRIØR CYCLIC DAMAGE",F9.3
&     //8X,"ACCUMULATED CYCLIC DAMAGE",F9.3)
      PRINT 350
  350 FØRMAT(//////)
      IF(C .EQ. B) GØ TØ 5
      STØP
      END

ØK
```

Figure A-1(b). Computer Listing of Accumulated Damage Calculation Program

ORIGINAL PAGE IS
OF POOR QUALITY

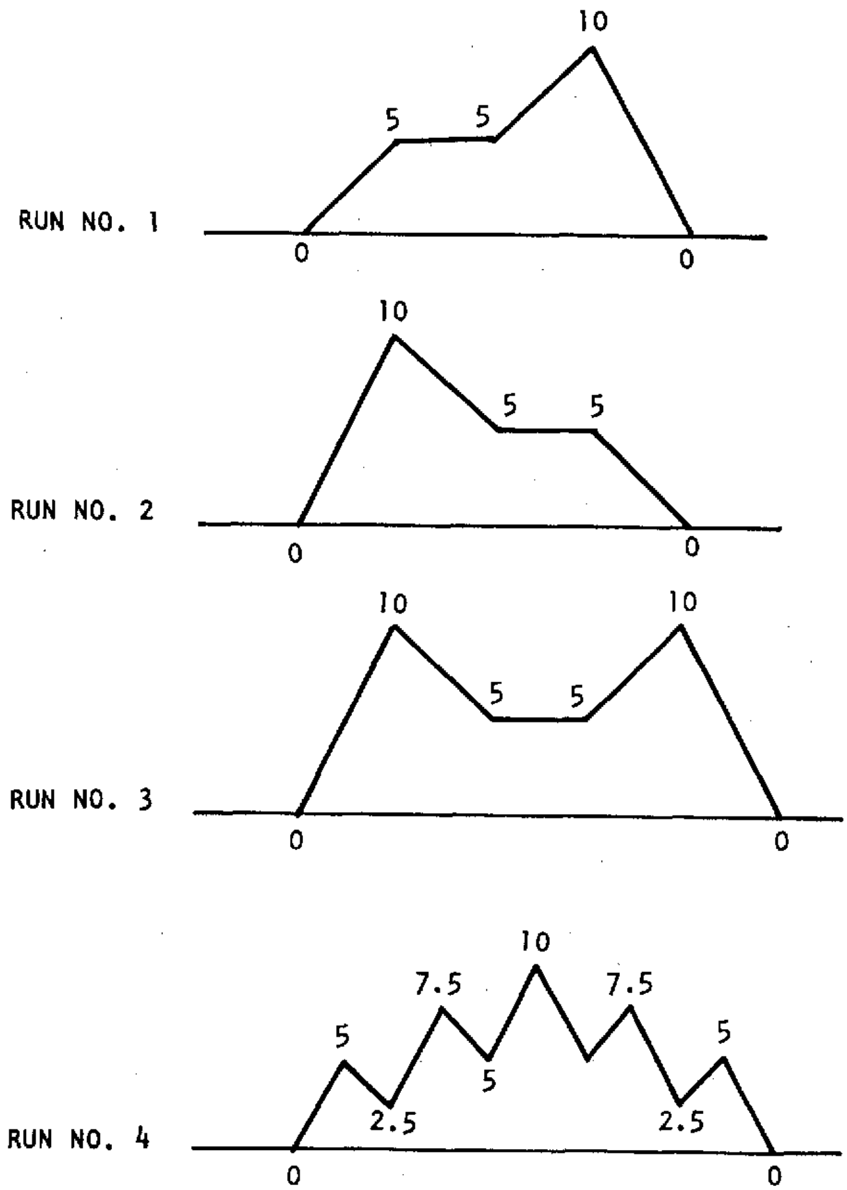

Figure A-2. Pressure History Used for Example Accumulated Damage Calculation

```
RUN

DAMAGE     10:40   NR T/S AUG 20, 1974

ENTER CØMPRESSØR ID
 ? TEST

 ENTER ACCUMULATED CYCLIC DAMAGE FØR CØMPRESSØR TEST
 ? 0

RUN ID?
 ? 1

DATA?
 ? 0 5000 5000 10000

RUN ID?
 ? 2

DATA?
 ? 0 10000 5000 5000

RUN ID?
 ? 3

DATA?
 ? 0 10000 5000 5000 10000

RUN ID?
 ? 4

DATA?
 ? 0 5000 2500 7500 5000 10000 5000 75000 2500+++++++ 2500 5000

RUN ID?
 ?
```

Figure A-3(a). Example of Accumulated Damage Calculation Computer Output

```
DAMAGE CALCULATIØN FØR CØMPRESSØR TEST

RUN        BLK   CYC    PMAX     PMIN      NE
1           1.    1.   10000.      0.     1.000

2           1.    1.   10000.      0.     1.000

3           1.    1.   10000.      0.     1.000
3           1.    2.   10000.   5000.     0.250

4           1.    1.   10000.      0.     1.000
4           1.    2.    7500.   2500.     0.187
4           1.    3.    7500.   2500.     0.187


       INCREMENTAL CYCLIC DAMAGE        4.625

             PRIØR CYCLIC DAMAGE        0.000

       ACCUMULATED CYCLIC DAMAGE        4.625




STØP

RUNNING TIME:    3.1 SECS   I/Ø TIME :    7.9 SECS

ØK



BYE

ØFF AT 10:44
```

Figure A-3(b). Example of Accumulated Damage Calculation Computer Output