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ATOMIC ENERGY OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

VALVE STEM PACKING SEAL TEST RESULTS FOR PRIMARY HEAT TRANSPORT SYSTEM CONDITIONS IN CANADIAN NUCLEAR GENERATING STATIONS

by

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Chalk River Nuclear Laboratories

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Résultats d'essais de joints de soupape à garniture de tige dans les conditions du système de caloportage primaire des centrales nucléaires canadiennes

par

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Résumé

Des essais de garniture de tige de soupape ont été effectués dans les locaux de Velan Engineering Companies Limited dans le but d'obtenir des données de performance pour les garnitures déjà en service dans les réacteurs CANDU-PHW* et pour d'autres types de garniture. La plupart de ces essais ont été répétés. Les résultats sont présentés pour dix garnitures mises à l'essai en deux modes de cycle de tige; les fuites, le tassement de la garniture et son frottement ont été les principales réponses.

Des essais de garniture ont été effectués avec de l'eau dans des conditions proches du système de caloportage primaire des réacteurs CANDU-PHW (288°C et 10 MPa), mais sans rayonnement ionisant. Les installations d'essai avaient des tiges montantes et rotatives. Les dimensions des boîtes à garniture étaient celles d'une soupape Velan standard; les garnitures étaient montées sur ressort pour compenser les contraintes appliquées.

Velan Engineering Companies Limited à Montréal a collaboré avec l'Energie Atomique du Canada, Limitée pour la conception des essais et le matériel d'essai. Les essais ont été effectués dans les locaux de Velan Engineering Companies Limited en vertu d'un contrat passé avec l'Energie Atomique du Canada, Limitée.

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* CANDU-PHW - Version de la filière Canada Deutérium Uranium où le caloporteur est de l'eau lourde pressurisée.

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SYNOPSIS

Valve stem packing tests were done at Velan Engineering Companies Limited to obtain performance data on packing already in CANDU-PHW* reactor service and on alternative packings. Most of the tests were replicated. Results are presented for ten packings tested under two stem cycle modes; leakage, packing consolidation and packing friction were the main responses.

Packing tests were performed with water at close to CANDU-PHW reactor primary heat transport (PHT) system conditions (288°C and 10 MPa), but without ionizing radiation. The test rigs had rising, rotating stems. Stuffing box dimensions were typical of a standard Velan valve; packings were spring loaded to control applied packing stress.

Velan Engineering Companies Limited in Montreal collaborated with Atomic Energy of Canada Limited on the design of the tests and the test equipment. The tests were conducted at Velan Engineering Companies Limited under contract to Atomic Energy of Canada Limited.

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* CANDU-PHW - CANada Deuterium Uranium-Pressurized Heavy Water

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LIST OF SYMBOLS

SYMBOL	DEFINITION	UNITS
f	friction coefficient between packing and stem, and between packing and stuffing box wall	-
h_o	initial packing height	m
Δh_1	change in packing height up to the start of test caused by the application of the axial precompression load and the initial application of load in the stuffing box	m
Δh_2	total change in the packing height up to the end of test	m
h	$h_o - \Delta h_1$	m
ℓ	accumulated relative movement between valve stem and packing	km
N	number of tests in a homogeneous group	-
Q	leak rate	cm^3/d
Q_7	seven day average leak rate for one test	cm^3/d
$\bar{Q}_7$	$\frac{\Sigma Q_7}{N}$, seven day grand average leak rate for a group of homogeneous tests	cm^3/d
$\bar{Q}$	grand average leak rate as a function of ℓ	cm^3/d
r_1	test rig stem radius	m
r_2	test rig stuffing box radius	m

SYMBOL	DEFINITION	UNITS
ρ	$\frac{s_{xy}}{s_x\, s_y}$, correlation coefficient which measures the degree of linear association between two variables x and y; the range is $-1 \leq \rho \leq +1$; for a high degree of association, ρ is close to -1 or +1	-
s^2	estimate of variance	depends on variable being analysed
s	estimate of standard deviation	depends on variable being analysed
σ_1	the axial stress applied to the packing prior to test either in the stuffing box or in a set of dies	MPa
σ_2	the axial stress applied to the packing throughout the test	MPa
t	time	weeks
T	packing friction torque	N.m
T_{max}	predicted maximum packing friction torque based on the 95% confidence limit of the student-t distribution of the measured breakaway torques	N.m
Y	ratio of radial to axial stress in a packed stuffing box	-
Z	a mathematical expression involving r_1, r_2, f and Y used in the derivation of the packing friction torque equation.	m^{-1}

1. INTRODUCTION

CANDU-PHW[a] reactors are cooled and moderated by heavy water which is relatively expensive. Valves, some with packed stems, are required in the heavy water systems to isolate equipment and/or auxilliary systems, and to control flow. The heavy water systems may contain radioactive contaminants. For economic and safety reasons, heavy water leakage through valve stem packing must be minimized and collected.

The Primary Heat Transport (PHT) system contains heavy water of the highest pressure and temperature in the nuclear generating station. Since valves in this system have the greatest potential for packing leakage, priority was given to developing improved stem seals on these valves. Based on tests at Chalk River Nuclear Laboratories (CRNL), a design procedure was established for the application of a particular packing which is the present reference material[b]. The performance of this packing has been determined through extensive testing (1, 2) and it is specified for PHT system packed valves. Information (3, 4) on the design procedure for applying valve packing is issued with the request for valve tenders.

A large number of other packing materials are commercially available but with no quantitative performance information. In an effort to increase the number of acceptable packings for Canadian nuclear service, it was necessary to compare performance of selected materials to the reference packing.

This report describes the results of some packing comparison tests done on a contract basis in the Velan Engineering Companies Limited laboratory as part of the Atomic Energy of Canada Limited packing test program. The results are specifically related to valves in the PHT system of CANDU-PHW reactors; however, with evaluation the results should be applicable to other hot water valves.

2. PROGRAM OBJECTIVES

(a) Test selected packings at simulated CANDU-PHW reactor PHT system conditions (excluding ionizing radiation) and compare performance with regard to:

(a) CANada Deuterium Uranium-Pressurized Heavy Water

(b) The reference material is coded as "Packing E" in this report.

(i) leakage

(ii) packing consolidation

(iii) stem friction

(iv) stem corrosion

(b) Determine if (how) total stem movement affects packing performance.

(c) Compare, qualitatively, three heat treatments of the 410 stainless steel (SS) stems with regard to corrosion.

(d) Generate a cooperative exchange of technical information between Atomic Energy of Canada Limited and Velan Engineering Companies Limited.

3. PROGRAM LIMITATIONS

The program was aimed at a specific application so did not investigate the effects of changing dimensional and system parameters. Extrapolation of the results to other service conditions should be done with caution. Time and cost limited the number of commercially available packings which could be tested.

4. PACKING MATERIALS

Packing materials (see Table 1) were purchased from the following manufacturers or their agents:

(a) Canadian Johns Manville Company Limited; Mississauga, Ontario.

(b) Chemical and Power Products Incorporated, New Jersey, U.S.A.

(c) Chesterton Canada Limited, Hamilton, Ontario.

(d) Crane Packing Company Limited, Hamilton, Ontario.

(e) Dixon Corporation, Rhode Island, U.S.A.

(f) James Walker and Company Limited, United Kingdom.

(g) Union Carbide Canada Limited, Toronto, Ontario.

Arrangements of the packings in the stuffing box are shown in Figure 1, and the physical appearance of some packings before and after test is shown in Figure 2.

Packing materials A and G were purchased in a continuous strand on a spool, so had to be custom cut to fit. Suitable packing rings were formed in a special set of dies at Velan Engineering Companies Limited.

Packings have been coded; a list identifying the packing materials according to tradename is issued by Atomic Energy of Canada Limited on a need-to-know basis.

5. EQUIPMENT

5.1 Description of Test Rigs

The test rigs are shown in Figures 3, 4 and 5. Six convective loops were supplied with water from one common nitrogen-over-water pressure source. A stuffing box, typical of a Velan "2 in." bonnetless globe valve[a], was connected to each loop. All the loops were equipped with strap-on heaters, and heat input was controlled by thermocouples sensing water temperature at the stuffing boxes.

The stuffing boxes had a primary and secondary packing with a leak-off in between. The packing was loaded with calibrated spring washers to set and control load. Strain gauged load cells were used to measure applied packing load.

Valve stems were stroked vertically in a rising, rotating manner with air motors. Stem motion was reversed by fluidic switches. The stem drive thread had 5.08 mm pitch and a stem stroke cycle was 38 mm in each direction. Rotational speed was 2 revolutions per minute (rev/min) approximately for the static tests and at various levels from 10 to 24 rev/min for the cycling tests.

Torque was measured by driving the stem with a torque wrench when the motor supply air was shut off.

5.2 Rig Dimensions

(a) Stem diameters were between 31.60 and 31.64 mm.

(b) A new stem with a 0.41 µm rms surface finish or better was used for each test.

(c) Stuffing box diameters were between 66.62 and 66.70 mm.

(d) Nominal packing cross-sectional area was 27.03 cm^2.

(a) bonnetless globe valve - all internal components in this style of valve are inserted through the stuffing box.

(e) Initial stuffing box surface finish was less than 0.41 μm rms.

(f) Diametral clearances were:

(i) between stem and gland, 0.89 to 0.94 mm

(ii) between stem and lantern ring, 0.61 to 0.79 mm

(iii) between stem and bottom ring, 1.60 mm.

5.3 Rig Materials

(a) The stems were all 410 SS but were subjected to three different heat treatments as described in Appendix A. The average hardnesses measured were:

Treatment A - Rockwell C 16.4

" 1 - Rockwell C 17.3

" 2 - Rockwell C 39.8

(b) The stuffing box was 316 SS.

(c) The packing gland was carbon steel.

(d) The lantern ring was 304 SS.

5.4 Leak Collection

Total leakage for the test period was collected from the lantern ring above the primary packing and condensed into a closed, glass cylinder graduated in cm^3. Total leakage and daily leak rates were recorded to the nearest cm^3.

6. TEST PLAN

6.1 Bilateral Comparisons

The program was bilateral to compare several packing materials at different stem operating conditions. When testing showed that a packing material was unsuitable, it was replaced in the program by another material from a priority list. It was intended that all tests would be triplicated at least; but for packing which failed and for packings substituted into the program, this was not always done.

The stem operating conditions were to be:

(a) Static

Stroke the stem in and out manually once each weekday.

(b) 50% Cycling

Stroke the stem continuously at approximately six cycles per minute for 12 hours each weekday.

(c) 100% Cycling

Stroke the stem continuously at approximately six cycles per minute for 24 hours each weekday.

Although the first few tests were done according to the original plan, for several reasons it was either undesirable or impractical to incorporate the stroking conditions outlined in (b) and (c). Most of the cycling tests were done stroking the stem for various periods during the eight hour working day only. Then the rigs were left static at temperature and pressure during the remaining 16 hours. All the cycling tests have been grouped for analysis purposes.

6.2 Test Conditions

6.2.1 Test Fluid

Test fluid was water.

Pressure	10 MPa
Temperature	288 ± 3°C
pH	10
Conductivity	$\lesssim$ 28 μS/cm^2

6.2.2 Test Period

Individual test length was initially six weeks but was reduced to five weeks after the first six tests. High leakage resulted in premature termination of some tests.

6.2.3 Packing Load

Individual packing rings were precompressed either in the stuffing box or in a special set of dies. The stress level depended on the packing type and was one of the following: 34.5, 68.9, 103.4 MPa. Axial packing stresses applied during tests are recorded in Table 2.

Spring washers controlled the packing load. To compensate for packing consolidation during test, the load was increased periodically back to the initial value. Readjustment was usually made every three to four days.

7. RIG ASSEMBLY AND TEST PROCEDURES

The detailed rig assembly and test procedure were established in an initial commissioning test run on all six test rigs. Usually all test rigs were started up simultaneously for a given test run.

Data were taken and recorded at least once each weekday usually between 0800 and 0900 hours. The sequence of data recording was:

(a) time

(b) accumulated leakage

(c) distance between the gland and the top of the packing chamber

(d) gland load

(e) water pressure

(f) water temperature

(g) number of completed stem cycles

(h) water pH

(i) temperatures along the packing chamber

(j) breakaway and running stem torques.

After these measurements were taken, the gland load was adjusted if necessary.

At the end of each test the packing chambers were dismantled and all parts were inspected. The condition of the stems and packing was noted.

8. SUMMARY OF TESTS

Fifty-nine tests have been evaluated and are summarized in Table 2. The six initial tests to commission the rigs are not included in Table 2 or the evaluation.

8.1 Leakage

When leakage increased rapidly and could not be controlled by adjusting the packing load back to the original setting, the packing was judged to have failed and the test was terminated. These rapid increases in leakage are not included in the data recorded in Table 2, but are described in Table 3. Figure 6 shows typical failure trends with Packing D.

8.2 Packing Consolidation

Packing consolidation is expressed as a percentage of the initial height except for Packing G. In this case, the packing manufacturer could not supply the material in the size needed to fit the annular width of the stuffing box, and as a substitute supplied a strand of larger size. The strand was accurately cut to the required length and die-formed into individual rings of rectangular cross section in a hydraulic press under a compressive stress of 103.4 MPa. The process was semi-automatic; rings were ejected from the die after being held at the maximum stress for about five seconds. The measured height of the formed rings was taken as h_o. Although no exact measurements were taken of Packing G as received from the manufacturer, the die-forming is estimated to have caused approximately an additional ten percent consolidation.

8.3 Packing Friction Torque

Stem torque was usually measured each working day. Four measurements were taken:

(a) breakaway torque when moving the stem outward,

(b) breakaway torque when moving the stem inward,

(c) running torque when moving the stem outward,

(d) running torque when moving the stem inward.

Breakaway torques were the highest values. By combining (a) and (b) the torque contributed by fluid pressure acting on the stem can be eliminated leaving a measurement of packing friction torque. A positive error due to stem drive thread friction is included in the packing friction measurements. This error is estimated to be less than one percent.

8.4 Test Idiosyncrasies

Although it was intended that the tests be run in a uniform manner, some variations in equipment and procedures either occurred or were adopted which may have influenced performance. In certain cases where early failure occurred with a particular packing, deliberate changes were introduced in an attempt to improve performance in later tests.

8.4.1 Undersized Stems

Five stems were inadvertently machined approximately 0.25 mm undersize on the diameter. The diameters ranged from 31.36 to 31.37 mm. These stems were used in tests No. 10, 24, 37, 38 and 51.

8.4.2 Packing Precompression

Packing F is composed of Packing D and Packing E. In test No. 47 only Packing E was precompressed to 68.9 MPa.

For Packing G, the precompression stress was increased in tests No. 50, 51 and 54 in an attempt to improve performance.

8.4.3 Packing Stress

For all tests on Packing E, the initial intent was to maintain a packing stress of 55.2 MPa. Test No. 39 was the first test run on Packing E; the initial packing stress was set at 55.2 MPa and held at that level for 15 days. However, the packing friction torque was much higher than expected so the rig drive was overloaded and damaged. The rig drive was repaired and the packing stress was reduced to 34.5 MPa on test day 15. The resulting frictional torque was low enough to permit the rig drive to function satisfactorily. A decision was made to run all later tests on Packing E at a packing axial stress of 34.5 MPa.

8.4.4 Variations in Packing D

Packing D was supplied in three different forms. In all tests except No. 29 the rings were cut on a diameter into two identical halves (see Figure 2); but in test No. 29, the rings were continuous and had to be installed over the top of the stem. For the last four tests conducted (No. 28, 33, 34, 35), the packing manufacturer supplied a 0.13 mm thick zinc washer with each packing ring (see Figure 2). The zinc was reputed to be a corrosion inhibitor. A zinc washer was installed above each packing ring for the four tests listed above.

8.4.5 Stem Rotational Speed

A few of the cycled stem tests were done at higher than the normal ten rev/min (see Table 2).

9. LEAKAGE RESULTS

9.1 Data Consolidation

Leakage for each test was grouped in seven day sequential periods (see Table 4) then averaged. Where common test conditions prevailed for a given packing material, a grand average and an estimate of variance were calculated for a given seven day test period. For instance, for Packing E, tests No. 40, 41, 42, 43, 44 and 45 were considered to have the same test conditions, whereas, test No. 39 was not included because the packing stress level was significantly different[a] from the other tests.

9.2 Estimate of Variance (s^2)

For a meaningful comparison of data groups, s^2 must be uniform. Examination of the leak rates showed that s^2 is an exponential function of $\bar{Q}_7$. Figure 7 displays the data for all packings. The fitted relationships are:

Static tests

$$s^2 = 0.375(\bar{Q}_7)^{1.385} \qquad \ldots(1)$$

correlation coefficient (6,7), $\rho = 0.91$

Cycled tests

$$s^2 = 0.889(\bar{Q}_7)^{1.940} \qquad \ldots(2)$$

$$\rho = 0.99$$

All tests combined (Figure 7)

$$s^2 = 0.681(\bar{Q}_7)^{1.659} \qquad \ldots(3)$$

$$\rho = 0.93$$

(a) For packing E, leak rate is a function of applied packing stress (1). The form of the relationship is $Q \propto \sigma_2^n$.

The value of n for packing E is about -7.

The scatter band is consistent over more than six orders of magnitude for s^2. That is, the range of average leak rate for any grand average is predictable.

For comparison purposes, leak rates were considered to be log-normal distributions. In log-normal distributions, variance is constant when based on logarithms of the response variable. The consistency of variance and the log-normal distribution[a] of average leak rates are illustrated in Figure 8 for the cycled stem tests on Packing E.

9.3 Trends

9.3.1 Static Stems

See Figure 9. No time trends were statistically significant. Packings A, B and C all leaked less than 1 cm^3/d and are not plotted. Only one test was done on Packing H; the average leak rate is shown in Table 2. Packing I failed prematurely in the one test done (see Table 3). The effect of packing stress on Packing G and Packing D is apparent in Figure 9.

The leak rate performance of Packing E at these operating conditions compares closely with the rate predicted from other tests (1,2,5[b]).

9.3.2 Cycled Stems

See Figures 10, 11 and 12. Results for Packings G, H, I and J are not plotted because premature failure occurred (see Table 3). All other packings exhibited trends which are caused by stroking the stems; this effect is confounded in Figure 10 since stroking rates were not consistent from test to test. Tests No. 29, 30/1 and 30/2 are not included in the grouped data for Packing D. The high stroke rates and stem speed have apparently resulted in abnormal leak response.

(a) The data were ordered according to the methods of Reference (8). In Figure 8, s^2 is based on logarithms of average leak rates.

(b) All the tests in Reference 1 were done on Packing E. In Reference 2, Packing E is coded as "Brand A". Reference 5 is based on unpublished data for Packing E tested under the following conditions:

σ_2 = 25.7 MPa   water pressure = 10.34 MPa

water temperature = 260°C   water pH = 10

The fitted relationships are:

Packing A

$$\bar{Q}_7 = \exp\left(\frac{t + 1.76}{0.22}\right) \text{ cm}^3/\text{d} \qquad \text{...(4)}$$

$$\rho = 0.89$$

Packing B

$$\bar{Q}_7 = \exp\left(\frac{t + 2.67}{0.60}\right) \text{ cm}^3/\text{d} \qquad \text{...(5)}$$

$$\rho = 0.92$$

Packing C

$$\bar{Q}_7 = \exp\left(\frac{t + 1.14}{1.19}\right) \text{ cm}^3/\text{d} \qquad \text{...(6)}$$

$$\rho = 0.96$$

Packing D

$$\bar{Q}_7 = \exp\left(\frac{t - 0.62}{0.62}\right) \text{ cm}^3/\text{d} \qquad \text{...(7)}$$

$$\rho = 0.99$$

Packing E

$$\bar{Q}_7 = \exp\left(\frac{t - 3.40}{0.25}\right) \text{ cm}^3/\text{d} \qquad \text{...(8)}$$

$$\rho = 0.93$$

Packing F

$$\bar{Q}_7 = \exp\left(\frac{t + 0.66}{0.68}\right) \text{ cm}^3/\text{d} \qquad \text{...(9)}$$

$$\rho = 0.99$$

Although leak rate is expressed as a function of time, the trends are due mainly to stem stroking. An attempt was made to isolate the stem stroke effect by determining leak rates for sequential periods of 1000 stem strokes completed (Figure 11). Packings A and B are not plotted because they exhibited a very low random leak rate ($< 1\ cm^3/d$). The stem stroke effect can be combined with the relationship in Figure 12 to express leak rate prediction equations in terms of total stem travel. The relationships are:

<u>Packing C</u>

$$\bar{Q} = \exp\left(\frac{\ell + 1.56}{1.15}\right)\ cm^3/d \qquad \ldots(10)$$

$$\rho = 0.99$$

<u>Packing D</u>

$$\bar{Q} = \exp\left(\frac{\ell - 0.72}{0.51}\right)\ cm^3/d \qquad \ldots(11)$$

$$\rho = 0.99$$

<u>Packing E</u>

$$\bar{Q} = \exp\left(\frac{\ell - 3.63}{0.21}\right)\ cm^3/d \qquad \ldots(12)$$

$$\rho = 0.97$$

<u>Packing F</u>

$$\bar{Q} = \exp\left(\frac{\ell + 0.43}{0.44}\right)\ cm^3/d \qquad \ldots(13)$$

$$\rho = 0.92$$

The prediction equations should be used with caution because:

(a) the cycling rate differed from test to test so the number of observations in each test and data group is not always the same,

(b) the number of cycles completed was not the same in all tests; as the number of cycles increased, less data was available for analysis,

(c) unidentifiable combined effects (e.g. time and stem cycles interaction) may be present.

10. PACKING CONSOLIDATION RESULTS

Packing materials consolidate under load; this is due to several factors among which are:

(a) collapse of voids,

(b) volatilization and dissolution of some constituents at operating conditions,

(c) stress redistribution due to operating conditions (e.g. stem stroking),

(d) loss of material by wear and/or extrusion.

Of principal concern is the amount of consolidation which occurs in-service. The rate of in-service consolidation has been recorded for some packings (2,4); it is rapid at first but approaches a zero rate within a few weeks. The amount of in-service consolidation for a particular packing depends on operating conditions such as packing stress, precompaction stress and operating temperature.

In-service consolidation must be known in order to design spring loaded packing glands within prescribed limits (4).

Analysis showed that in-service packing consolidation data for individual packings could be fitted by student-t distributions (7). Static and cycled tests were analysed separately and then grouped if no statistically significant difference in estimated means was apparent. Where comparisons could be made, Packings C and D were the only materials which had significantly different in-service consolidation for static and cycled tests.

Results are shown in Table 5. The maximum values shown are based on the 95% confidence limits of the student-t distributions. Estimates of the mean and maximum values for Packings F, H, I and J could not be made because of insufficient data.

11. PACKING FRICTION TORQUE RESULTS

Packing friction is a significant portion of the total load on a valve stem. Equations for determining packing friction torque have been derived (1). Measured friction torques have been analysed and adapted to the appropriate derived equation to provide suitable design information.

11.1 Data Grouping and Analysis

Friction torque measurements have been grouped according to:

(a) packing material,

(b) stem mode (static or cycled),

(c) packing stress.

Each group was examined for trends and was fitted to student-t distributions. It was found that where both static and cyled tests were done for a packing, higher friction resulted in the static tests. Predicted maximum friction torques are listed in Table 6; these are based on the 95% confidence limits of the student-t distributions. It is considered that these values are conservative for design purposes so no additional safety factor is needed.

Generally, trends were evident. In the static tests, friction increased with time and then stabilized; in the cycled tests, friction decreased initially and then stabilized. Even with the trends, good fits were obtained with student-t assuming data distribution about a mean. The most pronounced trends occurred with Packing C; Figure 13 shows the two tests which exhibited the greatest trends.

11.2 Packing Friction Coefficient and Axial to Radial Stress Ratio

The relationship (1) for determining packing friction is:

$$T = \frac{2\pi f \; Y r_1^2 \; \sigma_2}{Z} (1 - \exp(-Zh)) \qquad \ldots(14)$$

$$\text{where, } Z = \frac{2f \; (r_1 + r_2) Y}{r_2^2 - r_1^2} \qquad \ldots(15)$$

For the tests conducted, equations (14) and (15) reduce to the following.

$$T = 1.383 \times 10^{-5} \; \sigma_2 \; [1 - \exp(-114.53 \; f \; Yh)] \qquad \ldots(16)$$

Since T, σ_2 and h were all measured, it was possible to calculate the product, fY, for each packing. Values based on the predicted maximum friction torques are shown in Table 6.

12. STEM DAMAGE RESULTS

The test array is shown in Table 7. Typical examples of stem damage are shown in Figure 14. Results are grouped according to stem heat treatment and packing material.

12.1 Heat Treatment A

(a) Packing B

No corrosion was evident but abrasion (typified by test No. 12, Figure 14) occurred in the cycled tests.

(b) Packing C

No corrosion occurred.

(c) Packing D

In the static test, circumferential lines of pits occurred opposite the packing/gland interface and the packing/lantern ring interfaces (see test No. 25, Figure 14). No corrosion occurred in the cycled tests.

(d) Packing E

In the static test, a few pits occurred opposite the top of the lantern ring. No corrosion occurred in the cycled tests.

(e) Packing G

Pitted areas (test No. 48, Figure 14) were present.

(f) Packing H

Slight pitting occurred on both stems even though the cycled test was terminated after only one day.

(g) Packing I

Both tests were terminated early because of high leakage. No corrosion occurred.

12.2 Heat Treatment 1

(a) Packing A

The only corrosion occurred on one cycled stem. This was a narrow band of pits opposite the top surface of the upper packing.

(b) Packing B

No corrosion occurred but the cycled stems were abraded like the stems with Packing B in heat treatment A.

(c) Packing C

A few pits occurred in the region opposite the lantern ring on one cycled stem.

(d) Packing D

The static test with no zinc washers showed the most severe pitting. Corrosion was similar to test No. 25, Figure 14. The static test with zinc washers showed only a few pits. One of the cycled tests showed a few pits and the other had no corrosion. In all three cases where zinc washers were present, the washers below the lantern ring were completely oxidized while the washers above the lantern ring were unchanged.

(e) Packing E

No corrosion occurred in the static test and one of the cycled tests. Some pits occurred in the other two cycled tests (see test No. 43, Figure 14).

(f) Packing G

Stems from the static tests were pitted similar to the stem in test No. 48, Figure 14. The cycled test was terminated in five days because of high leakage; it still showed some pitting.

12.3 Heat Treatment 2

(a) Packing A

No corrosion occurred.

(b) Packing B

No corrosion or abrasion occurred in the static test. Both cycled stems were abraded similar to the stem in test No. 12, Figure 14. One cycled stem had a few pits opposite the region of the lantern ring.

(c) Packing C

No corrosion occurred.

(d) Packing D

The static test had no zinc washers; the stem was pitted in the region opposite the lantern ring (see test No. 26, Figure 14). For the two cycled tests without zinc washers, one stem was pitted and the other was not. In the cycled test with zinc washers, the stem was not pitted. Zinc washers below the lantern ring had completely oxidized while the washers above the lantern ring were unchanged.

(e) Packing E

All three stems were pitted similar to the stem in test No. 43, Figure 14.

(f) Packing F

Corrosion pits were present on both stems.

(g) Packing G

All three tests were terminated early because of high leakage. One of the cycled stems has a few corrosion pits opposite the lantern ring region. The other two stems were not corroded.

(h) Packing J

No corrosion occurred in the one short test.

12.4 Stem Damage Summary

Out of 59 tests, seven cases of slight stem wear occurred due to contact with metal parts in the stuffing box. This probably related to difficulty in centering the stem in the test rig at the start of test since the stem drive is mounted separately from the stuffing box. No effect on leakage or stem torque was apparent.

For all three heat treatments Packing B caused abrasion with the stems cycling. No other packing material caused abrasion with any stem heat treatment.

From a corrosion standpoint, tests were quite short and results are qualitative. Very little distinction with regard to heat treatment can be made, but heat treatment 2 appears to be slightly superior. In no case did corrosion have any identifiable effect on leakage or friction torque. This may result from the fact that corrosion pits fill up with packing lubricant (e.g. graphite) as the stems are stroked.

Pitting occurred in only one out of seven tests with Packing A and one out of nine tests with Packing B. In both cases the corrosion was slight. Both these PTFE packings extrude along the stem and stuffing box to some degree. It is postulated that this extrusion helps protect the stem. Significantly, Packing D when used alone caused corrosion with all three stem heat treatments in six out of eleven tests; whereas when Packing D was combined with Packing B, corrosion occurred in only one test out of nine. It is questionable whether the zinc added to Packing D provided protection during the tests; at any rate protection would be short lived since the zinc in the lower packing oxidizes quickly at operating conditions.

Packing C caused corrosion in only one test out of eight. However, this packing became very hard and at the end of each test was bonded to the stuffing box. A definite risk of stem damage during packing removal exists.

Packing E caused minor corrosion with all three heat treatments. Packing F was tested only with heat treatment 2 and minor corrosion resulted.

Packing G caused the greatest amount of corrosion of all packings tested. Insufficient data were obtained on Packings H, I and J to make judgements about corrosion.

This is inconsequential because these packings are unsuitable for PHT system conditions based on leakage performance.

13. RECOMMENDATIONS FOR PHT SYSTEM SERVICE

13.1 Suitable Packings

It has been established previously (1, 2, 9) that packings must be spring loaded to compensate for consolidation and to maintain load at an acceptable level; this controls leakage. Any packings recommended for Canadian nuclear service must be spring loaded according to specification (3, 4). Precompression of individual packing rings either in a special set of dies or in the stuffing box, reduces the amount of in-service consolidation.

(a) Packing A

This material was the best performer of the packings tested. At present Atomic Energy of Canada Limited specifies (3) Packing A for "600 lb ANSI* rated" service with a temperature limitation of 100°C. On the basis of the tests reported here, it is recommended that Packing A be considered for heavy water service at pressures up to 10 MPa and temperatures up to 290°C. The packing should be precompressed at about 69 MPa and spring loaded to about 34.5 MPa in service.

Packing A has a limited life in ionizing radiation; physical properties begin to deteriorate after an accumulated exposure of 2×10^5 rads (2000 Gy). This limit must be taken into consideration.

(b) Packing B

Packing B is specified (3) for control valves with either oxidized ** Zircaloy-2 or Inconel 625 stems in PHT systems. Tests (9) and performance (10) justify the selection. Packing B has the same limitation as Packing A for ionizing radiation.

The present specification (3) should not be expanded to include Packing B with 410 SS stems because of the abrasion damage experienced in the cycled tests. Stems of all three heat treatments were

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* ANSI - American National Standards Institute

** oxidized - The particular oxide is a hard, ceramic material formed according to a procedure developed at Atomic Energy of Canada Limited. Manufacturing technology is made available to control valve suppliers for the CANDU-PHW reactors.

affected. However, Packing B could be considered with 410 SS for applications where very limited stem stroking is expected (e.g. as typified by the static test conditions).

(c) Packing E

Performance at σ_2 = 34.5 MPa was predictable based on other tests (1, 2, 5). Packing E is the present reference material for PHT system service at a specified stress range of 69.0 MPa $\leq \sigma_2 \leq$ 82.8 MPa. In light of the present test results, it is recommended that the specification (3) be reviewed to consider the possibility of reducing σ_2 to somewhere between 34.5 MPa and 69.0 MPa. Reduced packing friction * with tolerable increase in leakage is the potential benefit.

Packing E should remain the reference material.

13.2 Promising Packings

(a) Packing D

Performance of Packing D was generally satisfactory. In static tests, leakage was very well controlled; but in a few cycled tests, failure was abrupt.

Packing D should be considered as a possible alternative material for PHT system service.

(b) Packing F

Performance was satisfactory for the two tests conducted. Packing F should be considered as a possible alternative material for PHT system service. Additional qualifying tests are needed before acceptance.

13.3 Rejected Packings

(a) Packing C

With respect to leakage, packing C performed satisfactorily in static tests but unsatisfactorily in cycled tests. In all tests, the packing became bonded to the stuffing box; this caused difficulty in packing removal.

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* Reduced packing friction - In some cases on power driven valves, it may be possible to specify lower powered (and therefore less costly) actuators by reducing packing friction.

(b) Packing G

For the tests reported here, this material proved to be unreliable. However, tests (4) at much higher packing stress ($69.0\ \text{MPa} \leq \sigma_2 \leq 82.8\ \text{MPa}$) yielded satisfactory results. The expense and time involved in additional tests to establish a minimum allowable packing stress are considered to be unjustifiable since several other packings show greater promise.

(c) Packings H, I and J

All three materials failed prematurely in an abrupt manner so are judged to be unreliable.

13.4 Stem Heat Treatments

Since the time these tests were planned, specifications for 410 SS valve stems in nuclear application have been updated. The latest information (11) does not include heat treatments A and 2 for valves in PHT service. Heat treatment 1 is included but the allowable stress specified (11) is not adequate for all valve stem applications. Velan Engineering Companies Limited use a heat treatment procedure (see Appendix A) which is covered by specification (11) and permits higher allowable stress than treatment 1.

On the basis of the corrosion witnessed in these tests, no judgement can be made whether the useful life of packing seals is affected in service. However, station maintenance personnel will be alerted to the fact that packing materials cause some corrosion of 410 SS valve stems. Conversion to a more corrosion resistant stem material could be the subject of an economic study incorporating a review of valve stem maintenance costs.

14. ACKNOWLEDGEMENTS

A.K. Velan took an active interest in the test program; he made many useful suggestions and brought the work to the attention of people throughout the power industry(12).

The authors thank D.B. Campbell for assisting with the preparation of the draft report.

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(11) Cases of ASME Boiler and Pressure Vessel Code. "Case N-62-2 (1621-2), Internal and External Valve Items, Section III, Division 1, 2 and 3 Line Valves". Approved in May, 1977.

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TABLE 1 : DESCRIPTION OF PACKING MATERIALS

Packing	Temperature Limit (a) (°C)	Packing Structure and Material Description
A	315	Woven Polytetrafluroethylene (PTFE) yarn.
B	290	Machined from solid, extruded PTFE rod and sandwiched between layers of packing D.
C	400	Woven chrysotile asbestos impregnated with a dry binder (unknown) and coated with WS_2.
D	815	Synthetic graphite laminations oriented perpendicular to the test rig stem axis.
E(b)	650	Woven chrysotile asbestos jacket reinforced with Inconel wire. The core is zinc powder, asbestos fines and graphite impregnated with styrene and butadiene rubber (SBR). Coated with graphite.
F	650	A combination of Packings D and E, with D sandwiched between rings of E.
G	not specified	Woven chrysotile asbestos jacket reinforced with Inconel wire and SBR. The core is asbestos fines, graphite, oxidized polyethelene resin and $NaNO_2$. Coated with graphite.
H	540	Compacted asbestos fibres, grease and mica.
I	510	A combination of two packings (a); both are woven chrysotile asbestos coated with mica. One is reinforced with brass wire and the other with Inconel wire.
J	260	Woven chrysotile asbestos saturated with PTFE suspensoid.

(a) Manufacturers recommendation.

(b) Packing E is the material presently specified by Atomic Energy of Canada Limited for PHT system packed valves.

TABLE 2 : TEST SUMMARY

PACKING	STEM MODE	TEST NO.	TEST CONDITIONS σ_1 (MPa)	σ_2 (MPa)	Test Period (d)	Stem Speed (rev/min)	Stem Heat Treatment (a)	Stem Strokes	LEAKAGE Total (cm^3)	Maximum (cm^3/d)	Average (cm^3/d)	PACKING CONSOLIDATION $\frac{\Delta h_1}{ho}$ x 100	$\frac{\Delta h_2}{ho}$ x 100
A	Static	1	69.0	34.5	34	2	2	25	0	0	0.0	11.1	12.4
		2	"	"	35	2	1	24	22	2	0.6	17.0	19.4
	Cycled	3	69.0	34.5	34	10	1	5334	2	1	0.1	12.1	13.9
		4	"	"	34	10	1	2210	5	1	0.1	17.0	18.4
		5	"	"	34	10	1	5000	12	2	0.4	15.0	17.1
		6	"	"	34	10	2	5000	20	2	0.6	14.2	16.5
		7	"	"	34	10	1	5000	20	2	0.6	14.4	16.8
B	Static	8	34.5	34.5	40	2	A	28	6	5	0.2	15.0	16.8
		9	"	"	34	2	2	24	4	1	0.1	17.8	18.2
		10	"	"	34	2	1	24	0	0	0.0	6.6	7.0
	Cycled	11	34.5	35.9	39	24	A	33,824	103	16	2.6	19.0	36.8
		12	"	34.5	42	20	A	12,450	24	4	0.6	18.0	27.2
		13	"	"	35	10	2	7,122	0	0	0.0	8.4	9.2
		14	"	"	34	10	2	4,090	5	3	0.1	7.4	7.8
		15	"	"	34	10	1	5,451	11	1	0.3	5.6	7.8
		16	"	"	34	10	1	3,297	8	1	0.2	7.4	8.4
C	Static	17	69.0	55.2	41	2	A	29	18	2	0.4	33.6	37.2
		18	"	"	35	2	2	28	8	4	0.2	31.8	35.2
		19	"	"	35	2	1	24	17	2	0.5	34.0	38.0
	Cycled	20	69.0	55.2	23	20	A	4852	229	55	>10.0	32.6	40.4
		21	"	"	34	10	2	7021	102	27	3.0	35.4	45.4
		22	"	"	34	10	2	4120	2926	379	86.1	31.0	38.2
		23	"	"	29	10	1	2951	492	100	>17.0	45.6	55.4
		24	"	"	34	10	1	3220	218	21	6.4	36.0	44.2
D	Static	25	34.5	35.9	40	2	A	29	22	8	0.6	28.8	30.8
		26	"	34.5	35	2	2	28	0	0	0.0	38.6	40.4
		27	0	"	34	2	1	23	12	2	0.4	22.6	26.6
		28	0	27.6	34	2	1	24	1086	80	31.9	23.8	26.4
	Cycled	29	34.5	34.5	16	20	A	4094	1054	820	> 65.9	37.4	41.6
		30/1	"	"	9	20	A	4602	1320	270	>146.7	-	-
		30/2	"	27.6	23	20	A	5700	653	140	> 28.4	39.4	45.2
		31	"	34.5	34	10	2	5140	337	79	9.5	40.2	45.0
		32	0	"	34	10	2	4476	1117	221	32.9	36.2	40.0
		33	0	"	34	10	1	3751	767	64	22.6	26.2	29.0
		34	0	"	34	10	1	5000	34	4	1.0	35.0	39.2
		35	0	"	34	10	2	5000	564	64	16.6	34.2	38.0

TABLE 2 : TEST SUMMARY cont'd.

PACKING	STEM MODE	TEST NO.	TEST CONDITIONS						LEAKAGE			PACKING CONSOLIDATION	
			σ_1 (MPa)	σ_2 (MPa)	Test Period (d)	Stem Speed (rev/min)	Stem Heat Treatment (a)	Stem Strokes	Total (cm^3)	Maximum (cm^3/d)	Average (cm^3/d)	$\frac{\Delta h_1}{ho}$ x 100	$\frac{\Delta h_2}{ho}$ x 100
E	Static	36	69.0	55.2	41	2	A	29	607	113	14.8	21.8	26.4
		37	"	34.5	34	2	2	25	1172	70	34.5	28.4	30.4
		38	"	"	35	2	1	23	1231	46	35.2	31.0	36.2
	Cycled	39	69.0	55.2	42	15-20	A	9,038	233	53	5.5	26.8	37.4
		40	"	34.5	40	20	A	12,722	1461	210	36.5	25.6	32.8
		41	"	"	34	10	2	4,127	1146	58	33.7	23.0	26.0
		42	"	"	35	10	2	7,122	294	17	8.4	25.6	27.8
		43	"	"	34	10	1	4,968	4594	270	135.1	25.8	32.0
		44	"	"	34	10	1	3,078	4074	280	119.8	25.8	30.4
		45	"	"	34	10	1	3,825	2551	156	75.0	24.6	28.8
F	Cycled	46	34.5	34.5	34	10	2	6961	294	37	8.6	26.6	31.2
		47	69.0	55.2	35	10	2	3973	105	14	3.0	23.0	26.8
G	Static	48	69.0	55.2	3	2	A	4	994	387	>331.3	16.2	18.8
		49	"	"	7	2	2	5	1417	260	>202.4	18.0	22.3
		50	103.4	"	34	2	1	25	4277	249	125.8	14.9	22.7
		51	"	"	35	2	1	24	6496	252	185.6	13.8	16.6
	Cycled	52	69.0	34.5	10	10	2	2624	4102	428	>410.2	16.1	17.5
		53	"	"	4	10	2	354	695	220	>173.8	11.6	12.1
		54	103.4	55.2	5	10	1	397	1610	325	>322.0	11.1	13.8
H	Static	55	69.0	55.2	41	2	A	26	593	28	14.5	8.2	10.6
	Cycled	56	69.0	55.2	1	20	A	866	-	-	-	7.0	19.6
I	Static	57	69.0	55.2	10	2	A	9	1340	290	>134.0	20.0	34.7
	Cycled	58	69.0	55.2	3	20	A	669	1223	480	>407.7	21.1	22.9
J	Cycled	59	34.5	34.5	1	-	2	0	-	-	-	18.4	-

(a) See Appendix A

TABLE 3 : LEAK RATES AT TIME OF PACKING FAILURE

Packing	Test No.	Days on Test	Stem Strokes	Leak Rate at Failure (cm^3/h)
C	20	23	4852	>250
	23	30	2951	>100
D	29	16	4094	>200
	30/1	9	4602	> 40
	30/2	23	5700	>100
E	39	43	9038	>300
G	48	4	4	(b)
	49	7	5	(b)
	52	11-18(a)	2624	>160
	53	5	354	>100
	54	6	397	>200
H	56	2	866	(c)
I	57	11	9	(b)
	58	4	669	(b)
J	59	2	0	>6000

Notes:

(a) The packing was considered to have failed on the eleventh test day. Leak rate spot checks taken on days 11 through 18 were all greater than 160 cm^3/h.

(b) Leak rate was persistently high from the start of test.

(c) The packing extruded out of the stuffing box causing gross leakage.

TABLE 4 : TOTAL LEAKAGE FOR SEVEN DAY SEQUENTIAL PERIODS

PACKING	STEM MODE	TEST NO.	TOTAL LEAKAGE (cm^3) IN 7 DAYS					
			Days 1-7	8-14	15-21	22-28	29-35	36-42
A	Static	1	0	0	0	0	0 (a)	-
		2	5	2	4	5	6	-
	Cycled	3	0	0	0	2	0 (a)	-
		4	0	2	1	1	1 (a)	-
		5	2	1	4	2	3 (a)	-
		6	2	5	6	3	4 (a)	-
		7	2	4	2	6	6 (a)	-
B	Static	8	5	0	1	0	0	0 (b)
		9	2	0	1	1	0 (a)	-
		10	0	0	0	0	0 (a)	-
	Cycled	11	2	2	13	25	48	13 (c)
		12	0	1	3	5	5	10
		13	0	0	0	0	0	-
		14	5	0	0	0	0 (a)	-
		15	0	1	2	4	4 (a)	-
		16	1	1	2	2	2 (a)	-
C	Static	17	8	3	2	1	2	2 (a)
		18	4	2	0	0	2	-
		19	3	3	2	4	5	-
	Cycled	20	5	4	163	(d)	-	-
		21	5	1	0	60	36 (a)	-
		22	17	23	373	1137	1376 (a)	-
		23	9	14	22	384	(d)	-
		24	10	17	31	52	108 (a)	-
D	Static	25	10	4	2	4	1	1 (b)
		26	0	0	0	0	0	-
		27	1	7	1	1	2 (a)	-
		28	160	129	172	442	183 (a)	-
	Cycled	29	4	80	(d)	-	-	-
		30/1	910	(d)	-	-	-	-
		30/2	212	183	114	(d)	-	-
		31	16	6	65	52	198 (a)	-
		32	22	12	116	351	616 (a)	-
		33	35	133	104	304	191 (a)	-
		34	3	5	4	8	14 (a)	-
		35	47	70	111	113	223 (a)	-

.../cont'd

TABLE 4 : TOTAL LEAKAGE FOR SEVEN DAY
Cont'd. SEQUENTIAL PERIODS

PACKING	STEM MODE	TEST NO.	TOTAL LEAKAGE (cm^3) IN 7 DAYS					
			Days 1-7	8-14	15-21	22-28	29-35	36-42
E	Static	36	16	279	130	65	62	55 (a)
		37	266	384	276	146	100(a)	-
		38	222	269	268	235	237	-
	Cycled	39	16	20	48	11	23	115
		40	543	246	143	193	163	173 (b)
		41	104	280	222	289	251(a)	-
		42	16	77	85	58	58	-
		43	229	983	1423	1237	722(a)	-
		44	322	301	840	1371	1240(a)	-
		45	211	228	519	815	778(a)	-
F	Cycled	46	8	30	51	72	133(a)	-
		47	4	4	12	28	57	-
G	Static	48	994(e)	(d)	-	-	-	-
		49	1417	(d)	-	-	-	-
		50	283	1172	1420	901	501(a)	-
		51	909	1275	1496	1565	1251	-
	Cycled	52	2266	(d)	-	-	-	-
		53	695(c)	(d)	-	-	-	-
		54	1610(b)	(d)	-	-	-	-
H	Static	55	64	102	72	97	133	125 (a)
	Cycled	56	(d)	-	-	-	-	-
I	Static	57	610	730 (e)	(d)	-	-	-
	Cycled	58	1223(e)	(d)	-	-	-	-
J	Cycled	59	(d)	-	-	-	-	-

(a) Six day total (b) Five day total (c) Four day total

(d) Failed (e) Three day total.

TABLE 5 : IN-SERVICE PACKING CONSOLIDATION

Packing	Stem Mode	σ_2 (MPa)	Packing Consolidation[(a)] %	
			Average	Maximum
A	Static	34.5	2.0	2.9
	Cycled	34.5	2.0	2.9
B	Static	34.5	1.1	2.5
	Cycled	34.5	1.1	2.5
C	Static	55.2	3.7	4.6
	Cycled	55.2	8.6	11.2
D	Static	34.5	2.6	4.9
	Cycled	34.5	4.2	6.0
E[(b)]	Static	34.5	4.3	8.4
	Cycled	34.5	4.3	8.4
G[(b)]	Static	55.2	4.0	8.8
	Cycled	55.2	4.0	8.8

(a) $\dfrac{(\Delta h_2 - \Delta h_1)\ 100}{h_o}$

(b) See Reference 2 for in-service consolidation at applied stress range of 68.9 to 82.7 MPa. In Reference 2, Packing E is coded as "Brand A" and Packing G as "Brand B".

TABLE 6 : PACKING FRICTION RESULTS

Packing	σ_2 (MPa)	h[(b)] (mm)	T_{max} (N.m)	fY	f[(c)]	Y
A	34.5	65.9	110	0.035	0.070	0.496
B	34.5	55.2	147	0.058	0.125	0.466
C	55.2	42.5	181	0.056	-	-
D	34.5	44.5	157	0.078	-	-
D	27.6	48.4	134	0.078	-	-
E	34.5[(a)]	44.6	162	0.081	0.185	0.438
F	34.5	48.9	113	0.048	-	-
F	55.2	46.6	158	0.043	-	-
G	55.2	59.4	167	0.036	0.135	0.269
H	55.2	58.3	164	0.036	-	-
I	55.2	55.9	125	0.028	-	-

(a) In test No. 39 with σ_2 = 55.2 MPa, the packing friction torque exceeded 240 N.m which resulted in damage to the stem drive. All later tests on Packing E were done with σ_2 = 34.5 MPa.

(b) Packing height was measured at the start of all tests.

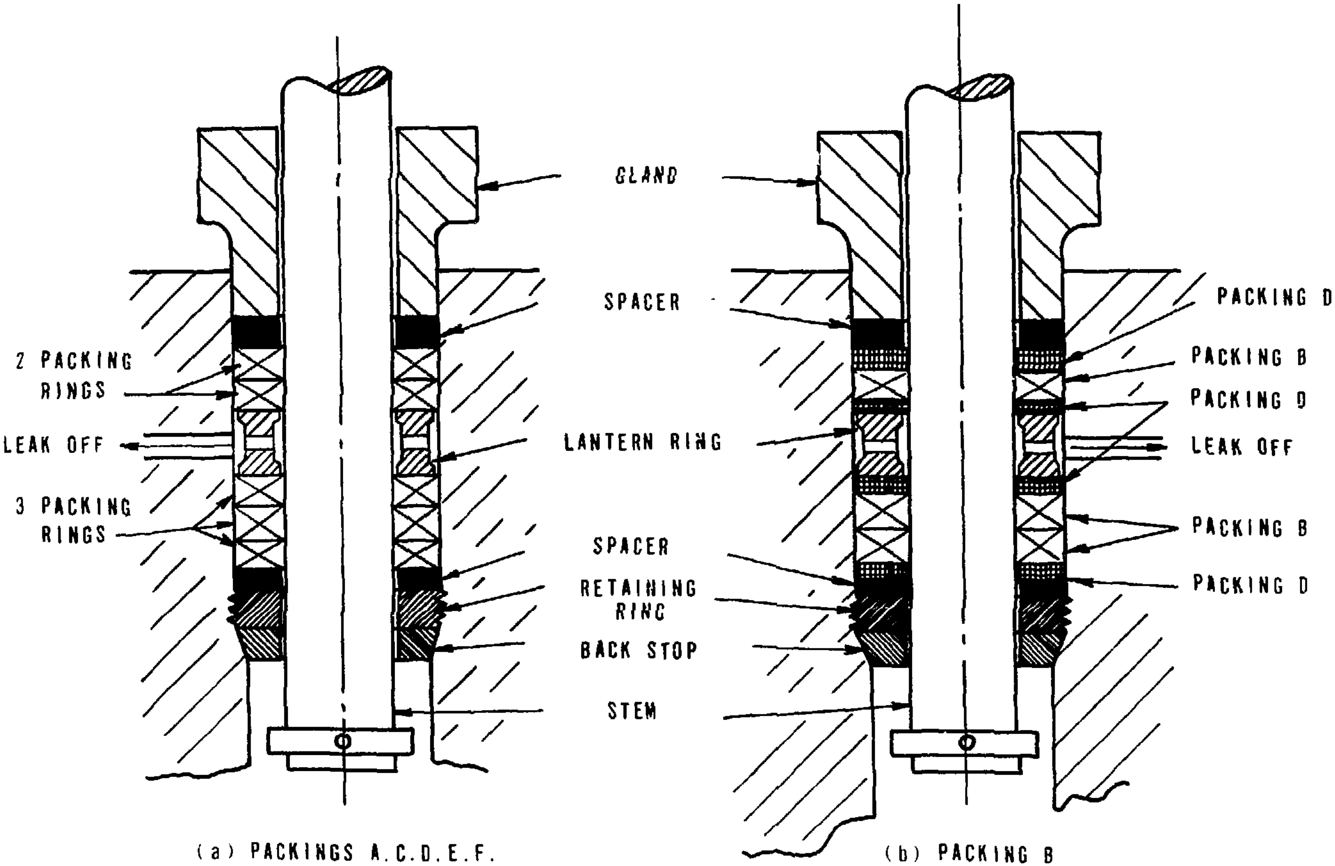
(c) Friction factor, f, was measured for several packings at Atomic Energy of Canada Limited.

TABLE 7 : NUMBER OF TESTS ARRANGED ACCORDING TO STEM HEAT TREATMENT AND PACKING MATERIAL

Packing	Stem Mode	Heat Treatment		
		A	1	2
A	static	0	1	1
	cycled	0	4	1
B	static	1	1	1
	cycled	2	2	2
C	static	1	1	1
	cycled	1	2	2
D	static	1	2 (a)	1
	cycled	2	2 (a)	3 (b)
E	static	1	1	1
	cycled	2	3	2
F	static	0	0	0
	cycled	0	0	2
G	static	1	2	1
	cycled	0	1	2
H	static	1	0	0
	cycled	1	0	0
I	static	1	0	0
	cycled	1	0	0
J	static	0	0	0
	cycled	0	0	1
TOTAL		16	22	21

(a) One static test and two cycled test had a zinc washer on top of each packing ring as a corrosion inhibitor.

(b) One cycled test had a zinc washer on top of each packing ring.



(a) PACKINGS A.C.D.E.F. G.H.I.J

(b) PACKING B

FIGURE 1 PACKING ARRANGEMENTS

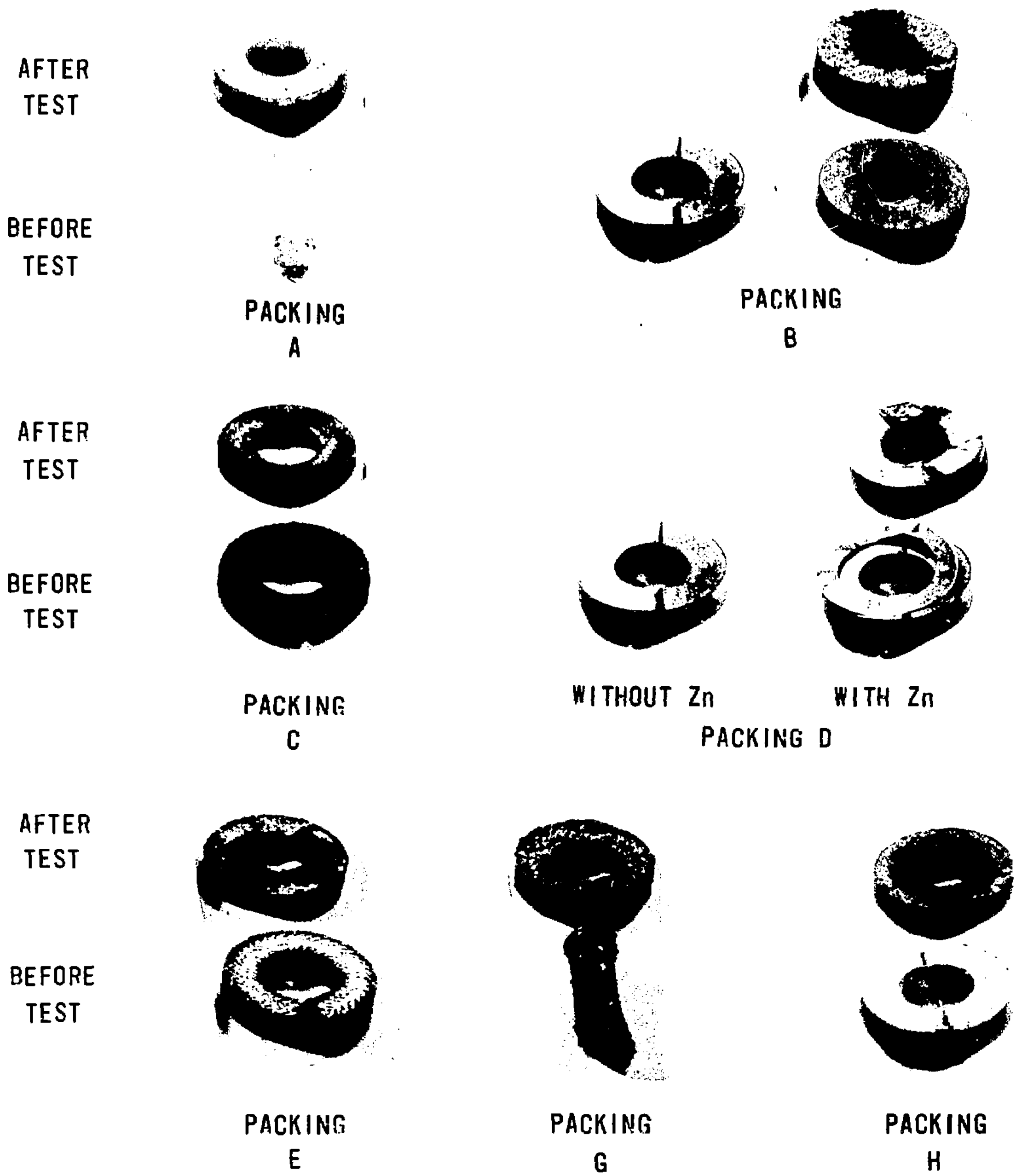


FIGURE 2 VALVE PACKING APPEARANCE BEFORE AND AFTER TESTING

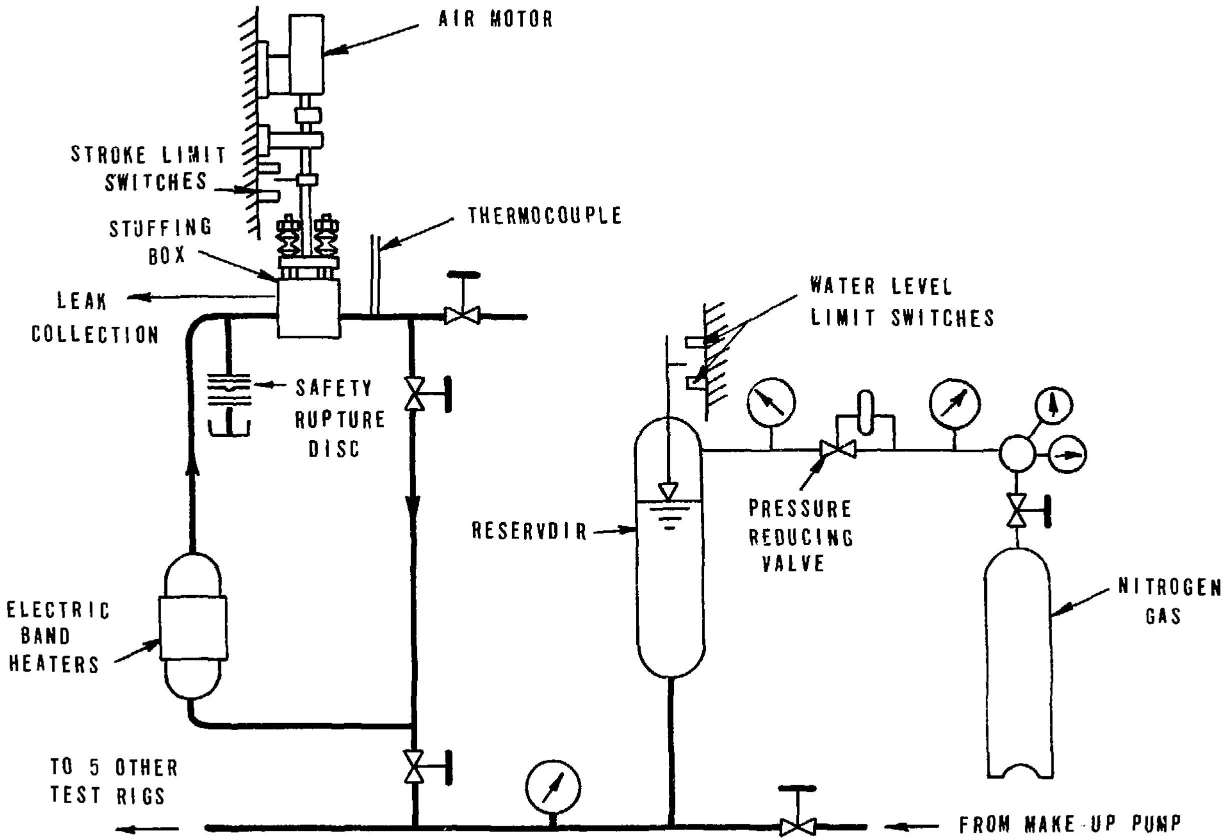


FIGURE 3 TEST SYSTEM SCHEMATIC

FIGURE 4 PACKING TEST RIGS

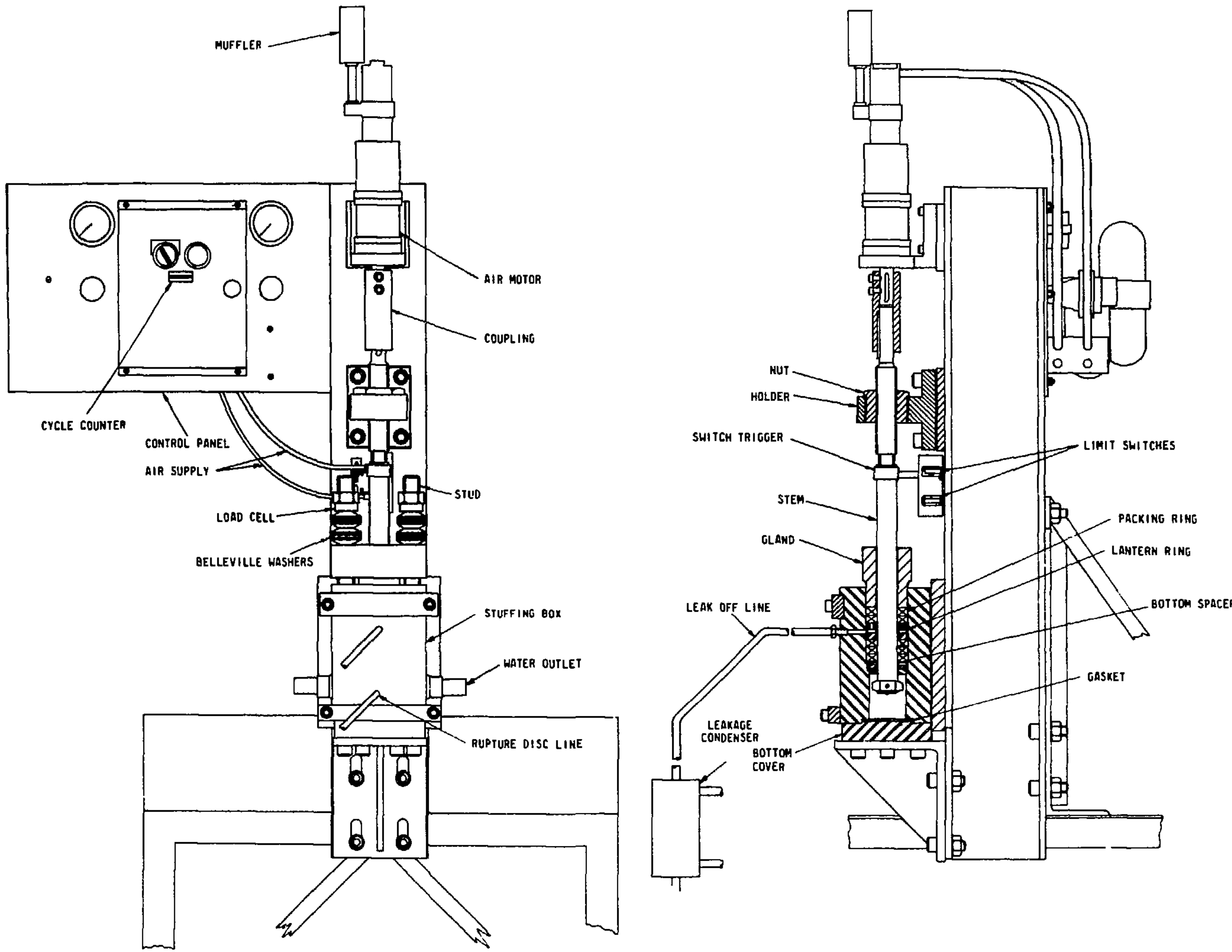


FIGURE 5 STUFFING BOX AND ACTUATOR ASSEMBLY

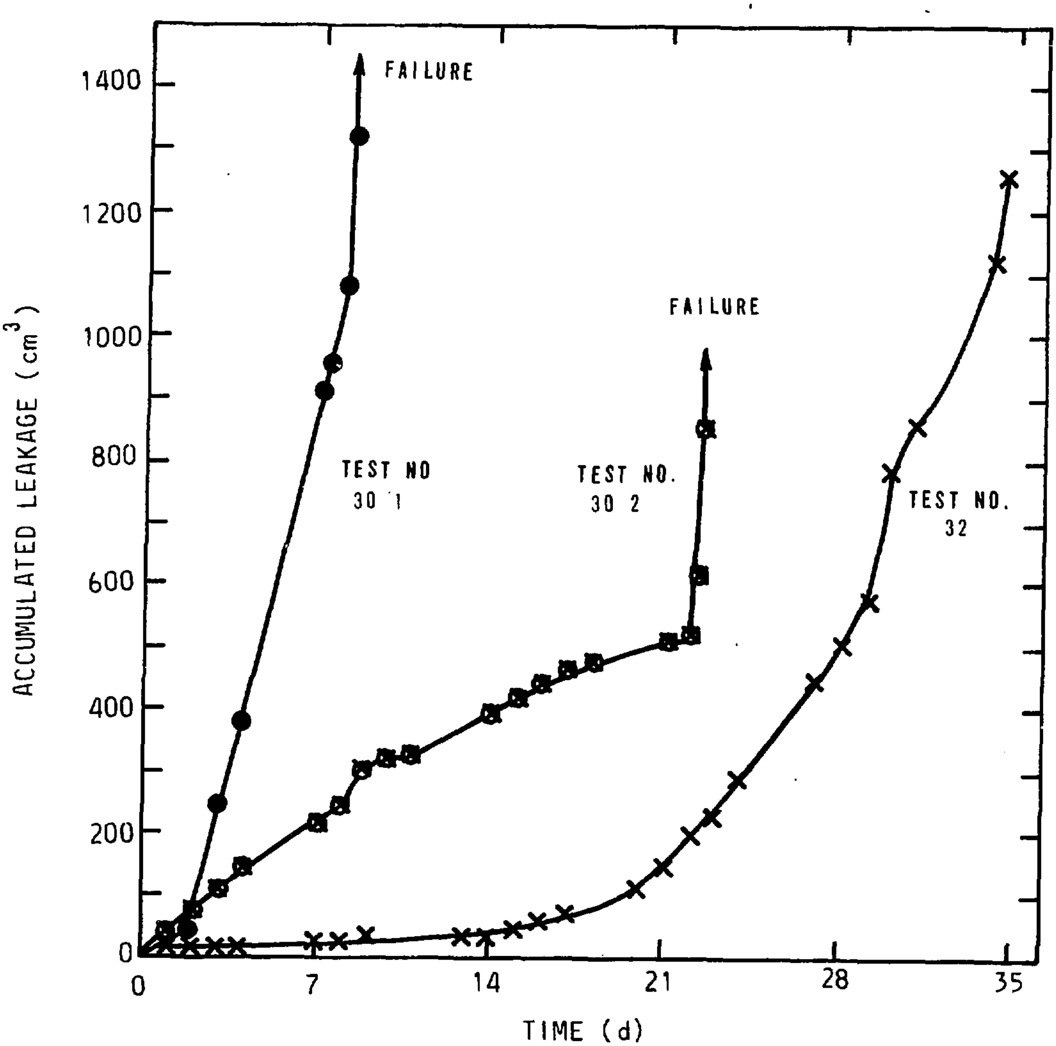


FIGURE 6 ACCUMULATED LEAKAGE SHOWING TRENDS TO FAILURE FOR SOME CYCLED STEM TESTS ON PACKING D

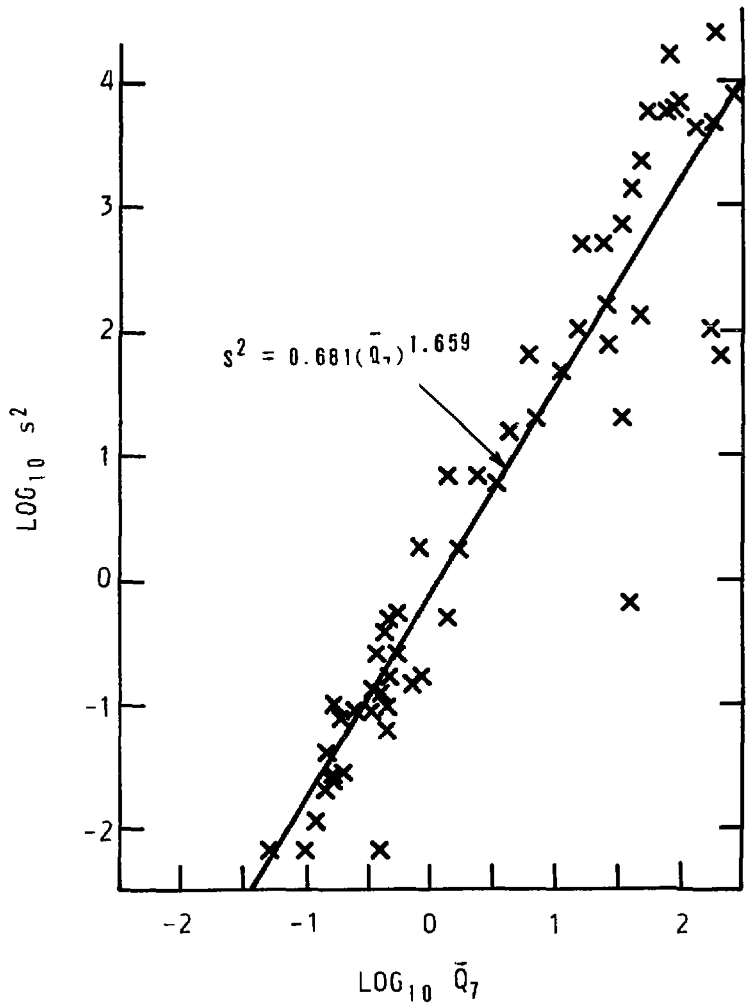


FIGURE 7 ESTIMATE OF VARIANCE AS A FUNCTION OF SEVEN DAY GRAND AVERAGE LEAK RATE FOR ALL PACKINGS

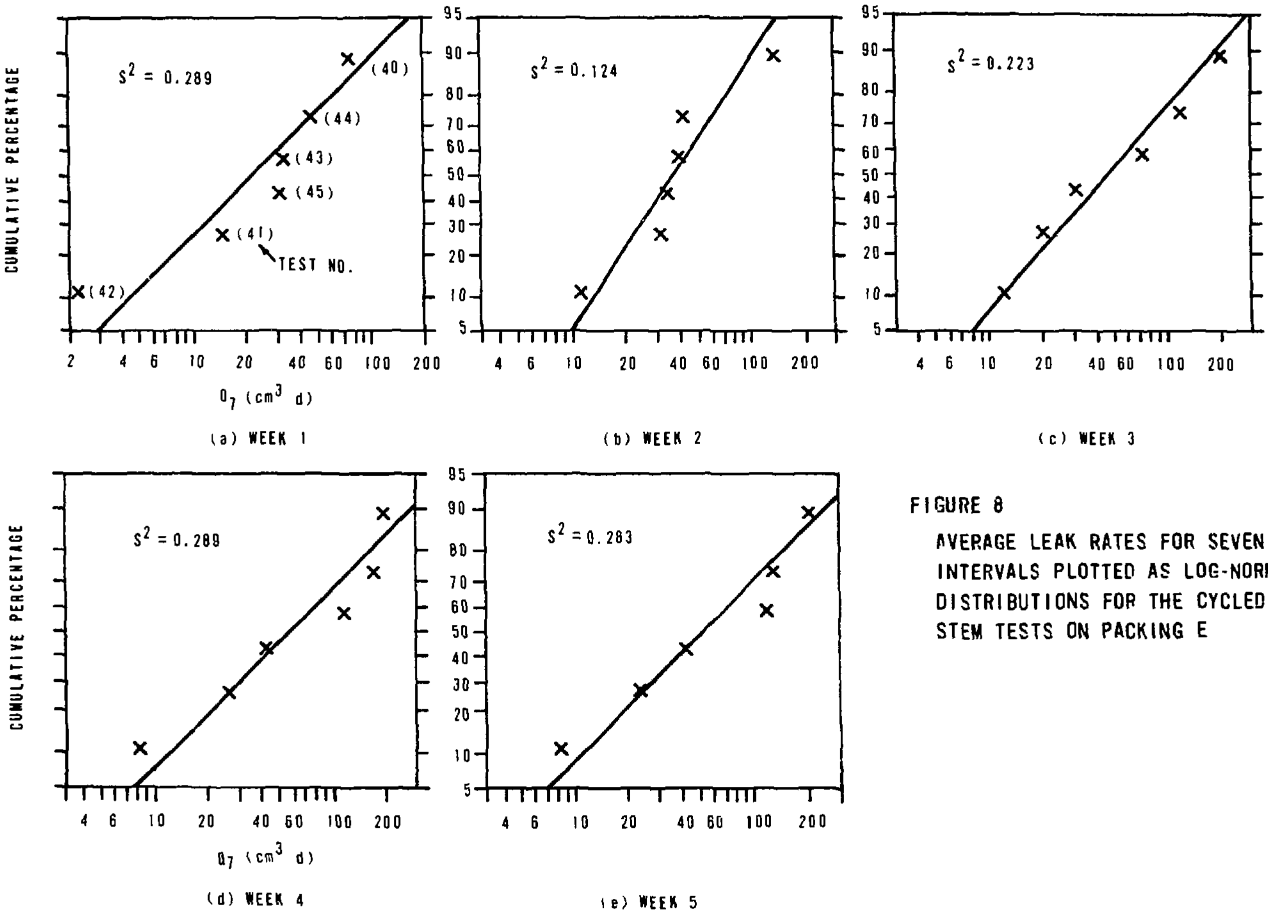


FIGURE 8

AVERAGE LEAK RATES FOR SEVEN DAY INTERVALS PLOTTED AS LOG-NORMAL DISTRIBUTIONS FOR THE CYCLED STEM TESTS ON PACKING E

FIGURE 8 AVERAGE LEAK RATES FOR SEVEN DAY INTERVALS PLOTTED AS LOG-NORMAL DISTRIBUTIONS FOR THE CYCLED STEM TESTS ON PACKING E

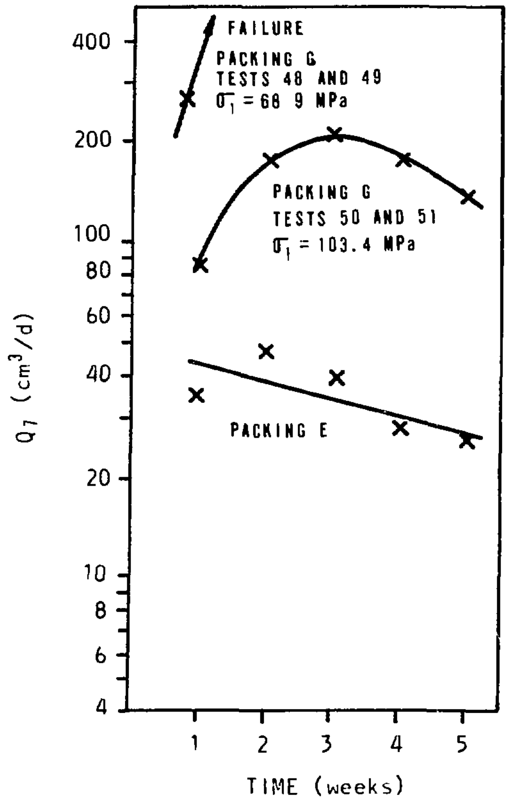
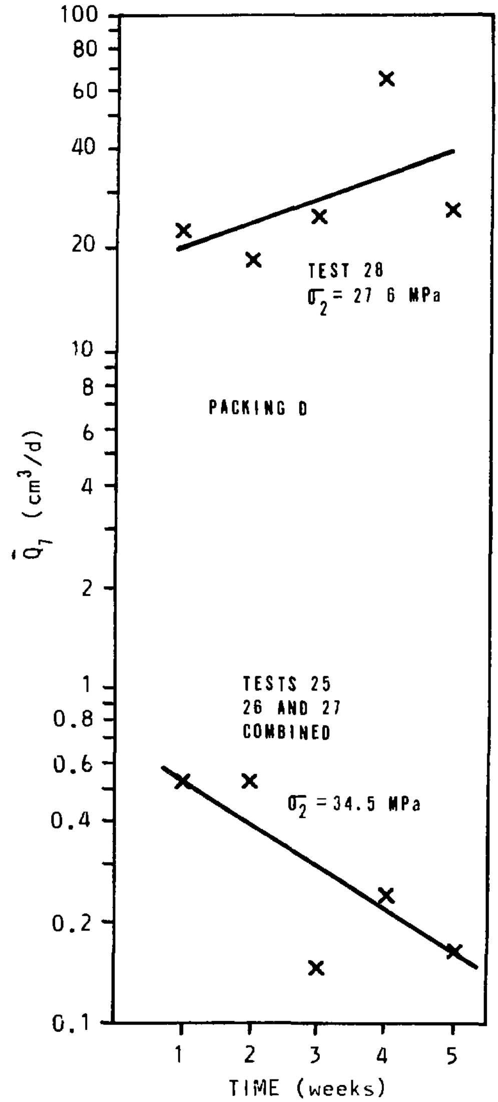


FIGURE 9 LEAK RATES FOR STATIC STEMS



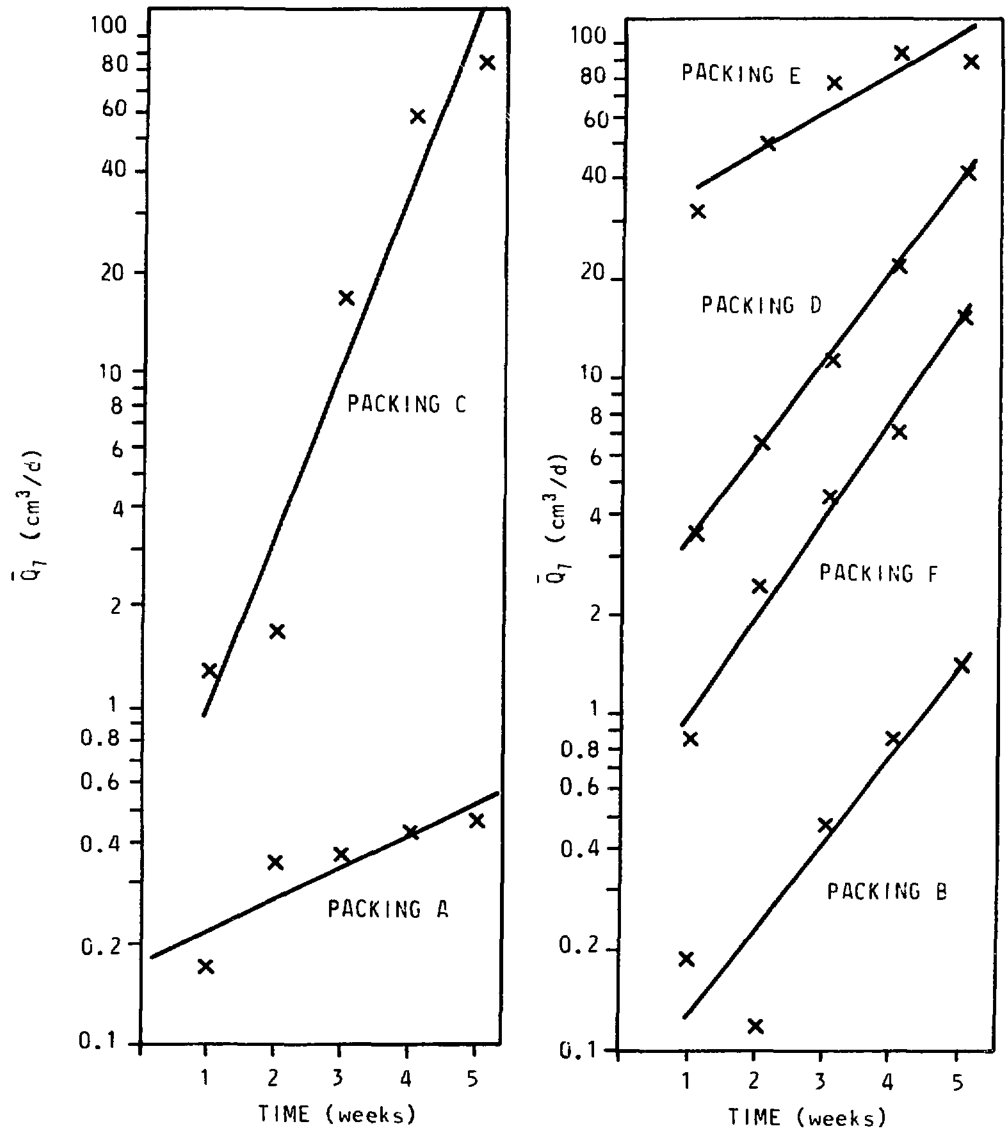


FIGURE 10 LEAK RATE TRENDS FOR CYCLED STEMS

NOTE: PACKING G FAILED PREMATURELY IN ALL CYCLING TESTS

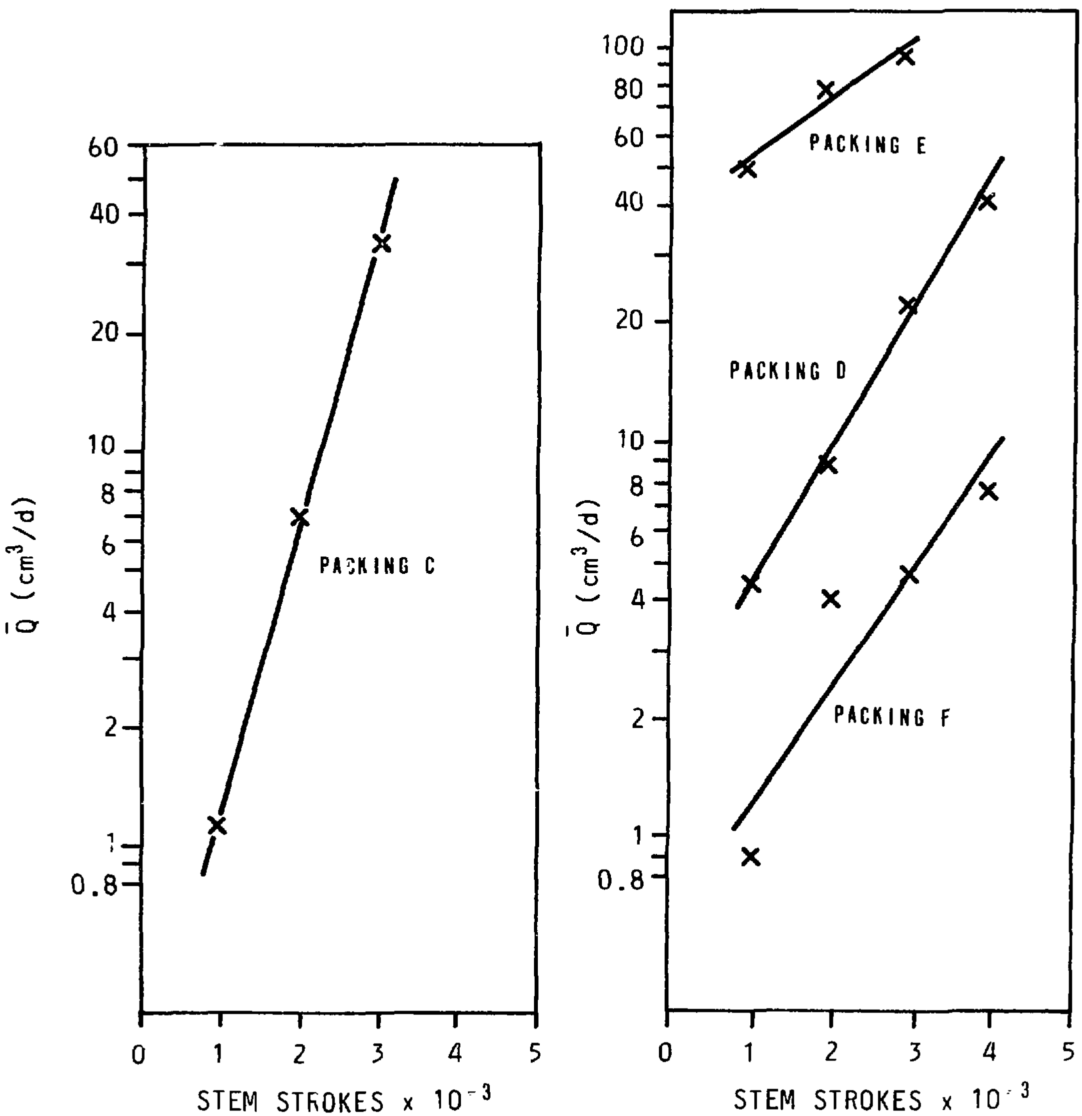


FIGURE 11 EFFECT OF STEM STROKES ON LEAK RATE

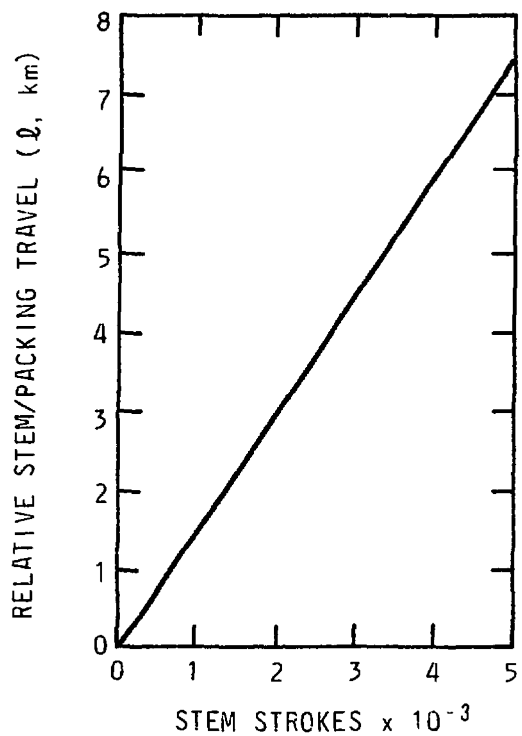


FIGURE 12 RELATIVE TRAVEL BETWEEN STEM AND PACKING vs NUMBER OF STEM STROKES

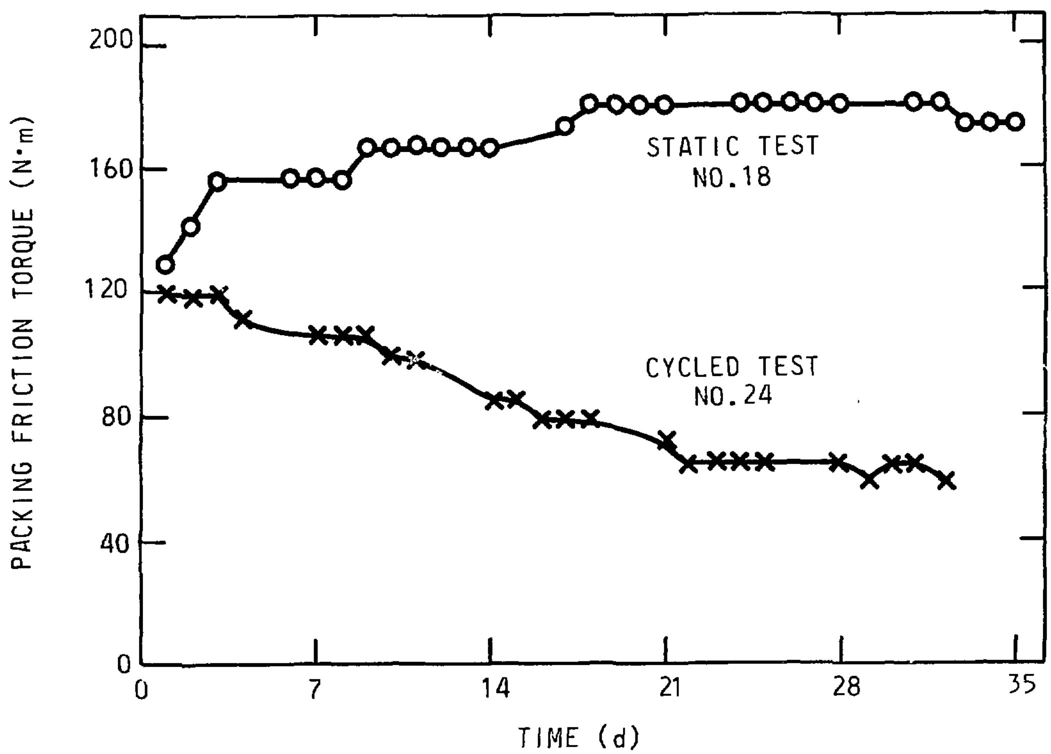
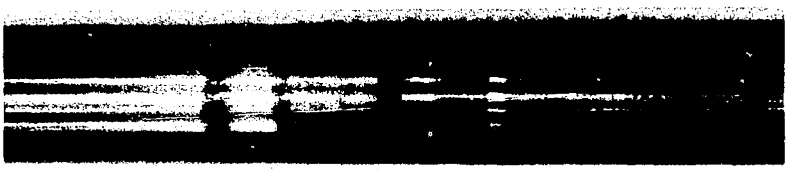
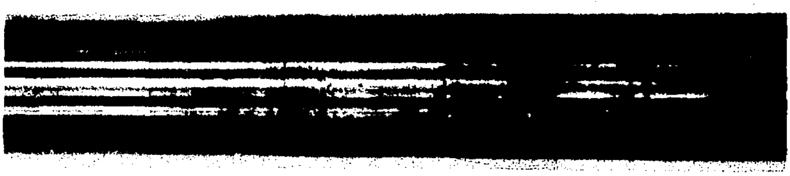


FIGURE 13 FRICTION TORQUE TRENDS FOR PACKING C

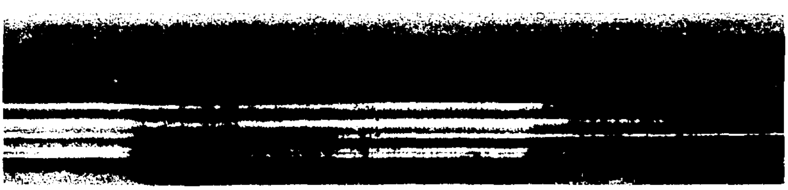
TEST NO. 12
PACKING B
ABRASION



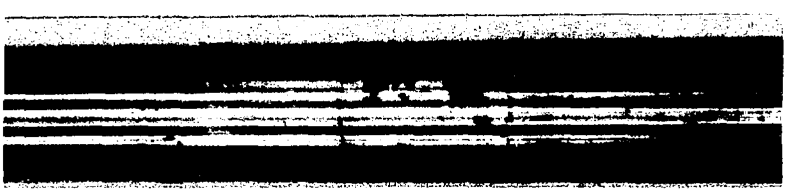
TEST NO 25
PACKING D
CIRCUMFERENTIAL LINES OF PITS



TEST NO 26
PACKING D
WIDE BAND OF CORROSION PITS



TEST NO. 43
PACKING E
NARROW BAND OF CORROSION PITS



TEST NO. 48
PACKING G
PITTED AREAS

FIGURE 14 EXAMPLES OF CORROSION AND ABRASION IN THE PACKING REGION ON TEST STEMS

APPENDIX A

STEM HEAT TREATMENTS

Stems subjected to three different heat treatments were tested. These treatments are designated A, 1 and 2. Table 2 indicates the heat treatment of the stem in each test. The same stem was used for tests 30/1 and 30/2; new stems were used in all other tests.

1. <u>Treatment A</u>

   The material was fully annealed as received from the material supplier.

2. <u>Treatment 1</u>

   According to steel manufacturers literature, in order to avoid severe loss of corrosion resistance and reduction of impact toughness in 410 SS, tempering should not be done in the temperature range 425-565°C. The procedure for treatment 1 was:

   (a) Heat to 955-1010°C and soak for 10 minutes.

   (b) Quench in a salt bath at 315°C and hold for 5 minutes.

   (c) Remove from the salt bath and air cool to 95°C.

   (d) Wash in 70°C water.

   (e) Immediately after washing, temper at 760°C for 2 hours.

   (f) Air cool.

3. <u>Treatment 2</u>

   The procedure was identical to treatment 1 except the temperature in step (e) was 370°C.

4. <u>Standard Velan Heat Treatment for 410 SS Stems</u>

   The procedure is identical to treatments 1 and 2 except the temperature in step (e) is a minimum of 593°C. The resulting hardness range is Rockwell C25 to C28. This treatment is believed to offer the best balance between toughness and strength.

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