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THE STRENGTH OF CLIMAX STOCK QUARTZ MONZONITE

W. B. DURHAM

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The Effect of Gamma Irradiation on
the Strength of Climax Stock Quartz Monzonite

W. B. Durham

ABSTRACT

A laboratory study was made of the effects of a massive dose of γ irradiation upon the mechanical properties of Climax stock quartz monzonite. Twenty-nine cylinders of rocks were tested using the Brazilian method and 26 strain gauged cylinders were tested to failure in uniaxial compression. One-half the cylinders in each group were subjected to a γ ray dose of 13.2 MGy (1.32×10^9 rads), or six times the maximum five-year dose to rock at the Spent Fuel Test-Climax, Nevada Test Site. The irradiation treatment lowered the ultimate compressional strength and lowered Young's modulus under uniaxial loads greater than 40 MPa. The treatment did not measurably affect the elastic behavior of the rock in compression, nor did it affect the Brazilian tensile strength. These trends suggest that the γ irradiation lowered the threshold stress at which microfractures begin to form. The irradiation has apparently not directly induced microfracturing in the rock, so a direct degrading effect on thermal and fluid transport properties is not expected.

INTRODUCTION

In conjunction with field testing the concept of safe long-term storage of spent nuclear fuel in an underground waste repository at the Spent Fuel Test-Climax underway at the Nevada Test Site (Ramspott et al., 1979), a laboratory study of the effect of radiation on rocks has been undertaken to assist the interpretation of field test results. Based on knowledge of existing studies of the effects of radiation on materials and on the nature of radiation emanating from the spent fuel assemblies, it was anticipated that generally the radiation would not have a significant effect on the rock at SFT-C. The present set of experiments was designed, therefore, to provide data under conservative conditions: dosages delivered were high and laboratory time was scaled downwards (to minimize time-dependent recovery) relative to SFT-C. The tested physical property was mechanical strength. Properties such as water permeability and thermal conductivity are of more direct interest to SFT-C, but mechanical strength is generally easier to measure in the laboratory and it is probably as good a diagnostic of radiation-induced effects. Changes in the heat and fluid transport properties of rock are usually a direct result of changes in its microcrack and crack structure and would therefore be expected to be accompanied by changes in mechanical strength.

SAMPLE PREPARATION

Starting material came from a section of 22" diameter core taken at the H-2 hole at the site of heater test number 1 in the Climax stock quartz monzonite, Nevada Test Site, roughly 100 m horizontally distant from the site of SFT-C. The mineralogy and petrology of the rock are described in Izett (1960). The particular material used came from approximately 1.5 m below the mine floor. Test samples 25.4 mm in diameter were cored from the starting material. Sample cylinder axes were all vertical. Sample diameters as cored varied by less than ± 0.01 mm and no further grinding was done on the cylindrical surfaces. The end surfaces were ground flat and parallel to ± 0.005 mm in most

cases. Twenty-six samples of 61 mm length were prepared for uniaxial compression testing and 29 samples 42 mm in length were prepared for Brazilian tensile testing. The sample numbering scheme was arbitrary, except that the suffixes "A" and "B" with the same number (see Table 1) indicate that the two particular samples were adjacent pieces from a single length of 25.4 mm-diameter core. Candidate samples were rejected only if material broke away during coring, cutting, or grinding. The presence of a dominant orthoclase feldspar phenocryst or of a through-going joint or mineral vein was not grounds for rejection.

EXPERIMENTAL PROCEDURE

Gamma irradiation. Gamma irradiation was carried out in the ^{60}Co irradiation pool at the LLNL Standards and Calibrations Laboratory. Details of the characteristics of the source are given in Elliott (1978). The source is made up of 72 ^{60}Co rods 190 mm long arranged in a circle 110 mm in diameter. The source lies at the bottom of a 6-m deep pool of deionized water. Within the empty cylindrical sample chamber formed by the ^{60}Co rods the radiation intensity varies by less than 10% in a symmetrically located volume 125 mm in height. The absorbed dose rate in the central volume of the ^{60}Co source, accounting for the moderating effect of water, is approximately 17 Gy/s (1700 rad/s). The dose rate was measured with radiochromatic dye film shortly before exposure of the rock samples. The measurement has an uncertainty of $\pm 10\%$. The expected maximum dose to rock over the 5-year duration of SFT-C, 2.2 MGy (Wilcox and Van Konynenburg, 1981), is achieved in the ^{60}Co source in about 1.5 days. All samples irradiated in the present study were held in the γ cell for nine days ± 30 min., where they absorbed a total dose of 13.0 ± 1.3 MGy (1.3×10^9 rads).

Primary γ ray energies of the ^{60}Co source and of the spent fuel canisters are both of the order of 1 MeV, where the dominant energy transfer mechanism is expected to involve Compton interactions. Therefore, no direct enhancement of damage per rad is expected at higher dose rates. However, if a time-dependent recovery of damage occurs, laboratory scaling to shorter times would tend to make damage in the laboratory samples higher for a given absorbed dose, in keeping with the conservative design of the test. Page (1979) has found that at least one γ ray-induced change, in thermoluminescence, can be reversed over time. Time was considered to be an important variable in the tests and to minimize possible effects of time-dependent recovery, the delay between irradiation and mechanical testing was kept brief.

The size of the sample chamber in the γ cell allowed irradiation of up to 10 samples at a time, in the arrangement shown in Fig. 1a. Samples were in direct contact with the water in the cell. Tensile samples were irradiated in two groups (10 samples followed by 5 samples) as were the compression samples (10 samples followed by 4 samples). To compensate for the slight attenuation of γ rays across the samples (the mean free path of 1.25 MeV γ rays is roughly 60 mm) and for the possibility of vertical mispositioning of the samples with respect to the horizontal symmetry plane of radiation intensity, the samples were rotated according to a preplanned schedule (Fig. 1b) three times during irradiation. Rotation required the samples be out of the cell for 10 ± 5 min.

The control samples were handled in four groups (10 followed by 4 tensile, 10 followed by 2 compression) corresponding to the γ groups. They were placed and arranged in the same type of open canister as were the γ samples, but instead of being lowered into the pool, the control samples were placed alongside the pool in a stainless steel bucket filled with water from the γ pool. The water was dumped back into the pool and replaced with new pool water each time the γ samples were removed for rotation.

Following irradiation, γ samples and their corresponding control samples were wiped dry and placed together in the same box for transport and storage. The Brazilian tests were carried out between 2 and 4 days following removal from the water (details in Table 1) and no effort was made in the interim to speed the drying of the samples. Compression samples were handled similarly. They were stored for 3 (in one case) or 4 (in the other case) days without handling prior to strain gauging and were tested at 7-14 days out of water. Further details of the timing are given in Table 2. Two biaxial sets of strain gauges were bonded with epoxy directly to the cylindrical surface of each compression sample 180° from each other. The samples were not jacketed. The biaxial gauges were oriented to measure axial and circumferential strain. The two axial gauges were wired in series, as were the two circumferential gauges, in order to cancel local effects due to bending.

Mechanical testing. A treatment of Brazilian tensile testing and the equations involved is given by Jaeger and Cook (1976, p. 169). The Brazilian tests here were carried out using a manually controlled hydraulic press. The test column between platen faces consisted of hardened steel spacers, a load cell, the sample, and two pieces of stiff paperboard approximately 0.5 mm thick on either side of the sample. The paperboard, which spreads out the line load on the sample surface and smoothes microscopic asperities, has a negligible systematic effect upon the stress distribution in the sample (Jaeger and Cook, 1976, p. 171). Steel shims were used to establish a column parallelism of $\pm 10 \mu\text{m}$ along the sample. New pieces of paperboard were used for each run but otherwise the positioning and orientation of column parts was kept constant. A force-displacement record for each test was made on an x-y recorder to which were wired the load cell and a displacement transducer between platen faces. Elapsed time was measured with the sweep-second hand of a wristwatch and was penciled on the force-displacement

record every minute. Loading rates were 1.0 ± 0.3 MPa/min (measured as maximum tensile stress). The order of testing was based on "random" selection from the storage box prior to each test. Irradiated samples take on a distinctive grayish hue (Page, 1979) and it turned out to be impractical to mask from the operators the nature (γ or control) of the current sample.

Testing of the more heavily instrumented compression samples was only slightly more complex. Again, a manually controlled hydraulic press applied the load and again a displacement transducer and load cell wired to an x-y recorder provided a real time graphical display of the progress of each test. Additionally, the strain gauges and a second force gauge fed more precise information to a computer which stored the data and displayed it at a control terminal. The computer also recorded clock time as measured by its internal clock. Longitudinal strain rates before ultimate failure varied from 2 to $4 \times 10^{-6} \text{ s}^{-1}$. The compression column consisted of the sample, the two load cells, various spacers of tungsten carbide ground to precision flatness and parallelism, and a 0.25 mm layer of aluminum foil at the top of the column to smooth asperities. Precise alignment of coaxial column parts was established with phenolic alignment jigs at each contact of two column parts. The alignment jigs at either end of the sample overlapped the sample by approximately 9 mm. Again, no changes were made in the column from run to run except for the exchange of samples. Test samples generally were alternated between γ and control and, again, no attempt was made to mask the identity of the current sample.

RESULTS

Brazilian tensile tests. The results for 29 tensile tests are given in Table I. Tensile strengths varied from 9.0 to 15.2 MPa. Strengths for the 15 irradiated samples had a mean of 11.9 MPa $\pm$ 1.5 MPa standard deviation. Strengths for 14 control samples

measured 11.4 ± 1.8 MPa. The Student's t-test on these statistic indicates a low probability (less than 0.5) that the data on the 29 rocks have sampled two different populations. The Wilcoxon signed ranks test (Conover, 1980), a more reliable test because it requires fewer assumptions regarding the data distribution, also cannot detect a difference between the two groups.

Compression tests. Some typical data from the compression tests are shown in Figure 2. The results for all 26 samples are summarized numerically in Table 2. Young's modulus ($E \equiv \text{longitudinal stress/longitudinal strain}$) showed enough of a linear behavior at low longitudinal strains ($\epsilon_L < .04\%$) and high strains ($\epsilon_L > .1\%$) that two values for E usually provided a satisfactory summary. The two values in Table 2 are $E_1 = E(\epsilon_L < .04\%)$ and $E_2 = E(\epsilon_L > .1\%)$. In most cases, Poisson's ratio ($\nu \equiv \epsilon_{\text{radial}}/\epsilon_L$) was not constant with ϵ_L but since it usually did plot as a straight line over most of the elastic region, two parameters for ν were again usually a satisfactory description.

The trends among several mechanical properties of the γ and control groups are gathered in Table 3. The dependence of ultimate strength upon radiation treatment stands out most clearly. Fourteen irradiated samples had a mean strength of 163.7 MPa and a standard deviation of 35.2 MPa. The 12 control samples had a strength of 204.4 ± 33.4 MPa. On the basis of the Wilcoxon test it can be stated that there is a strong probability that the γ irradiation treatment has degraded the ultimate strength and has augmented the change, $\Delta E = E_2 - E_1$, in Young's modulus. An effect upon ν , E_1 , or E_2 cannot be distinguished with statistical significance.

The data also allow study of temporal variations of the parameters. Plotted in the order of testing (Fig. 3) the strength appears to decrease with time for both groups of samples, γ and control. Linear least squares fits to the data plotted as strength vs sequence and strength vs calendar time (Table 4) show that the correlation with sequence

is better. When the independent variable is time out of water instead of calendar time (recall that the compression samples went through irradiation in two groups), the linear correlation is even lower. Non-parametric tests of correlation, which rely only on relative rank of the data values, give high probability that a correlation exists. The Kendall test (e.g. Conover, 1980, p. 256) indicates the probability of no correlation of strength vs sequence (or vs. calendar time) for γ and control as 8% and 20%, respectively. The combined probability of no correlation less than 2%.

Error. The purpose of making repeat measurements and of making a comparative rather than an absolute measurement was to reduce the time and expense of error analysis. Measurement equipment was not specially calibrated for this work, but great pain was taken to maintain unchanged the state of all of the experimental hardware. The measurements were carried out in as brief a time span as possible. It must be concluded that the predominant cause of random error is sample variation.

With what certainty can we say that the "treatment" referred to above involved purely the introduction of γ irradiation? The only time γ and control samples were physically separated was during the 9-day exposure period and a few hours prior to the treatment. During the irradiation, both groups resided in the same room in water from the γ pool, physically separated by a vertical distance of 5 m and a horizontal distance of 1-2 m. The γ group was exposed to the entire pool of water which circulates slowly while the control group rested in a few liters of stagnant pool water which was changed periodically. The possibility that the degradation in strength came from heating is unlikely. The γ ray energy deposited in the rocks, roughly 1.5 W per sample, causes them to heat macroscopically, but since the rocks are bathed in water, they are cooled very efficiently. The temperature of the pool water is 2 to 3 K above room temperature (where the control samples rested) and the temperature of the water-

filled canister immediately upon retrieval from the γ cell was not more than 5 K above pool water temperature. The rocks undoubtedly experienced temperatures above 310 K in the Nevada desert or warm Livermore summer.

The correlation between strength and sequence (or time) for both the γ and control groups (Table 4, Fig. 3) means that a systematic error is very likely (probability near .98) present in the data. The fact that a linear correlation with testing sequence is better than a linear correlation with time suggests the problem lies not with physical or chemical changes in the rocks, but in the testing hardware. A plausible explanation lies in the behavior of the phenolic column guides. The guides surrounded the first 9 mm of the outer diameter of each end of the samples. In the first tests, the guides fit rather tightly, but the fit became looser later on due to the circumferential stretching of the samples. For the last few tests, the guides were actually split. Since the effect of a tight vs a loose fit is a higher confining stress, be it only over a short length of the sample, and since confining stress has a well known ameliorating effect on the brittle strength of rock, it is possible that the rocks became weaker because the guides became less constrictive.

The most pertinent observation regarding the correlation, whatever its cause, is that it exists in the control samples as well as the γ samples. Even if the correlation is the result of a physical or chemical time-dependent change in the rock, that change does not seem to depend on whether or not the rock was γ irradiated, and the basic findings of this study are intact. In fact, the systematic strength change has had the effect of widening the standard deviation of the data with respect to the standard deviation of the real population; hence subtracting out the systematic trend would lead to stronger statistical support for the conclusion that γ irradiation has a degrading effect on the unconfined compressive strength of the rock.

DISCUSSION

The list of physical properties which have been affected by the γ irradiation treatment vs those which have not tantalizly begs speculation into basic mechanisms of inelastic deformation of rock. Even with the preliminary sorts of data generated here, several meaningful inferences can be made:

1. The mode of failure under compressive loading is different on the microscopic scale from that under Brazilian tensile loading.
2. There is an inconsistency among the individual statistical indications in Table 3.
3. It is not reasonable that $\Delta E = E_2 - E_1$ is affected by γ irradiation while E_1 and E_2 , taken individually, are not. Based on the Wilcoxon test (Table 3), the most probable, physically consistent set of events is that E_1 was not affected by the irradiation and that E_2 (and therefore ΔE) was degraded by the irradiation. As indicated in Table 3, the probability that the observed effect upon ΔE is a sampling quirk is 4%. If E_2 is degraded, one can infer that one effect of γ irradiation is that it has allowed void formation (presumably microfracturing) to occur at lower levels of stress. Ultimate failure of rocks in compression is generally understood in terms of increased numbers and lengths of microfractures (Kranz, 1979; Wong, 1982), so a lowering of ultimate strength following γ irradiation is consistent with the trend in ΔE . Furthermore, because of their close relationship to microfracturing, changes in permeability (an increase) and in thermal conductivity (a decrease) would be expected at lower stress levels in irradiated rock as compared to non-irradiated rock.

3. Since E_1 and v were not significantly affected by γ irradiation, the treatment given the γ group probably did not create directly any new surface within the rocks (such as fractures, open or tightly closed) and therefore would not be expected to have a direct effect upon several other physical properties of interest to waste storage: thermal conductivity, thermal diffusivity, and permeability.

Representative failed samples were given a cursory physical examination and nothing was found which contradicts any of these inferences. Except for the color change, Brazilian tested samples, irradiated and unirradiated, were indistinguishable to the eye and to the scanning electron microscope (SEM). The damage to these samples was dominated by the single vertical macrofracture. The microfractures observed were few in number and were generally parallel to and within a few hundred μm of the main fracture.

The compression samples showed a distinct difference between irradiated and non-irradiated. The macroscopic failure surfaces in the control group tended to give the fragments a columnar appearance, that is, large vertical fractures were fairly prevalent. The γ group samples had more of a tendency to form a more classic single high angle macroscopic shear fracture. Fragments of the γ samples were typically more competent than fragments of the control group samples. Seen in the SEM, the density of microfractures was similar for the two groups, although fractures in the control group tended to be more open, as might be expected of less competent rock (Fig. 4). Much of the difference can be explained by the fact that the control samples failed at higher stress, hence they contained considerably more strain energy at the moment of catastrophic failure. The roughly equivalent densities of microfractures in the two groups

lends support to inference 3) above. The γ samples did not see as high stress as the control samples, yet they contain as many fractures; hence it is plausible that the γ samples began microfracturing at a lower level of stress.

CONCLUSION

An experiment has been conducted to determine whether or not a dose of γ irradiation, 13.2 MGy (1.32×10^9 rads) or 6 times the total maximum dose to rock of the 5-year SFT-C, has an effect on certain mechanical properties of Climax Stock quartz monzonite. The following conclusions can be drawn regarding the behavior of the rock at 0.1 MPa:

- 1) The γ -irradiation treatment does not affect the Brazilian tensile strength.
- 2) The treatment does not affect the elastic behavior of the rock.
- 3) The treatment does lower the threshold stress where microfractures begin to form, with a resultant decrease, relative to non-irradiated rock, in Young's modulus under load and in ultimate strength (Table 3). Above the threshold stress it is likely that permeability is higher and thermal conductivity is lower relative to non-irradiated rock. The threshold stress is above 20 MPa at atmospheric pressure and is doubtless higher under the higher lithostatic stresses encountered underground. It does not seem likely therefore that these degrading effects of γ irradiation would be noticed in an underground nuclear waste repository.

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Table I -- Brazilian tensile tests

<u>Sample</u>	<u>Order of testing</u>	<u>Y group or control group</u>	<u>Tensile strength (MPa)</u>
110B	17	Y	13.8
111B	6	Y	12.2
112B	27	Y	14.2
11A	11	Y	10.4
11B	15	C	12.5
12A	24	Y	12.0
12B	18	Y	11.7
13B	2	C	10.2
16A	9	C	11.1
16B	8	C	11.5
17A	25	Y	9.0
17B	7	Y	9.8
18B	12	Y	11.7
21A	29	Y	11.5
21B	22	C	12.2
22A	19	C	10.4
22B	21	Y	12.9
23A	5	C	12.2
23B	13	C	12.5
24A	14	C	10.5
24B	10	C	13.8
25A	23	C	11.9
25B	20	Y	11.3
26A	28	C	12.0
26B	4	Y	12.9
27A	16	C	15.2
27B	1	Y	14.0
28A	3	Y	11.1
28B	26	C	6.8

irradiation dates:

1-20 11/11/81 - 11/20/81

21-29 11/23/81 - 12/2/81

testing dates:

1-10 11/23/81

11-20 11/24/81

21-29 12/4/81

TABLE 2 — Compression tests

Sample	Order of testing	Y group or control group	Young's modulus, E, GPa		Poisson's ratio, ν		Calendar time D:MM:NN	Ultimate failure	
			E_1 c _L * < 0.04%	E_2 c _L > 0.1%	ν_0 †	ν (c _L = 0.1%)		c _L †	σ_{ult} , MPa
111A	15	Y	53.3	71.0	.29	.27	27:08:10	3450	220
112A	8	C	59.0	69.7	.205	.24	26:10:10	3230	223
13A	25	C	63.8	74.5	.24	.33	29:13:38	3280	201
14A	24	Y	50.9	61.4	.21	.22	29:13:05	2520	141
15A	11	Y	69.2	74.8	.22	.27	26:13:19	3230	229
18A	18	C	48.5	53.5	.31	.31	27:09:39	2600	128
310A	7	Y	49.4	67.3	.10	.16	26:09:10	3100	164
311A	19	Y	37.9	49.8	.075	.10	27:10:49	3090	104
311B	2	C	55.2	73.5	.17	.20	25:10:49	3560	246
312A	10	C	43.5	66.1			26:11:28	3660	172
312B	23	C	70.0	74.5	.23	.245	29:11:22	3120	216
31A	21	Y	45.3	64.7	.20	.215	29:09:50	3130	189
31B	16	C	66.8	72.7	.205	.235	27:08:41	2300	184
32A	12	C	46.6	81.0	.09	.15	26:13:52	3160	231
32B	5	Y	84.2	87.2	.23	.27	25:15:30	1610	165
33A	14	C	39.4	73.2	.05	.175	26:15:42	3460	229
33B	9	Y	66.9	76.4	.14	.18	26:10:39	2640	189
34A	20	C	40.1	32.6	.085	.135	27:11:15	3870	191
34B	17	Y	61.4	70.7	.055	.11	27:09:08	2130	137
35A	22	Y	36.5	60.5	.225	.20	29:10:52	2960	162
35B	3	Y	76.4	80.3	.26	.275	23:13:03	2030	170
36A	13	Y	32.6	50.2	.18	.295	26:14:54	2500	119
37A	1	Y	42.1	55.6	.13	.19	23:09:45	3150	162
38A	26	Y	40.5	59.2	.11	.16	29:14:11	3570	141
39A	6	C	25.2	60.7	.13	.13	26:08:17	3100	194
39B	4	C	62.2	79.4	.12	.155	25:14:15	3370	238

† projection to c_L = 0 of tangent at c_L = 0.1% (see Figure 2)

irradiation dates:

1-20 1/4/82-1/13/82, 1100 hrs
 21-26 1/13/82-1/22/82, 1615 hrs

testing dates:

1-5 1/25/82
 6-14 1/26/82
 15-20 1/27/82
 21-26 1/29/82

Table 3 — Mechanical properties vs γ irradiation

Brazilian tests				Compression tests									
Tensile strength (MPa)		σ_{ult}^{pl} (MPa)		$E(\epsilon_g < 0.4\%) = E_1$ (GPa)		$E(\epsilon_g > 1\%) = E_2$ (GPa)		$E_2 - E_1 \equiv \Delta E$ (GPa)		$\nu(\epsilon_g = .1\%)$		$\sigma_{ult}^{pl}/\epsilon_g^{pl}$ (GPa)	
γ	control	γ	control	γ	control	γ	control	γ	control	γ	control	γ	control
13.8		220		53.3		71.0		17.7		.27		63.77	
12.2			223		59.0		69.7		10.7		.24		69.04
14.2			201		63.8		74.5		10.7		.33		61.28
10.4		141		50.4		61.4		11.0		.22		59.24	
	12.5	229		69.2		74.8		5.6		.27		70.90	
12.0			128		48.4		53.5		5.0		.31		49.23
11.7		164				67.3		17.9		.16		52.90	
	10.2	104		37.9		49.8		11.9		.10		33.66	
	11.1		246		55.2		73.5		18.3		.20		69.10
	11.5		172		48.5		66.1		17.6				46.99
9.0			216		70.0		74.5		4.5		.25		69.23
9.8		183											
11.7			184		66.8		72.7		5.9		.24		80.00
11.5			231		46.6		81.0		34.4		.15		73.10
	12.2	165		84.2		87.2		3.0		.27		102.48	
	10.4		225		39.4		73.2		33.8		.18		66.18
12.9		189		66.9		76.4		.5		.18		71.39	
	12.2				40.1		58.3		18.2		.14		49.35
	12.5	137	191			70.7		9.3		.11		64.32	
	10.5	162		61.4		69		23.5		.20		54.73	
	13.8	170		36.5		76.4		80.5		.28		83.74	
	11.9	119		76.4		50.2		17.6		.21		47.60	
11.3		162		32.6		55.6		13.5		.19		51.43	
	12.0	181		42.1		59.2		18.7		.16		39.50	
12.9				40.5									
	15.2		194		25.2		60.7		35.5		.15		62.38
			238		62.2		79.4		17.2		.16		70.62
14.0													
11.1	6.8												
11.9 $\pm$ 1.5**	11.4 $\pm$ 1.8	163.7 $\pm$ 35.2	204.4 $\pm$ 33.4	53.3 $\pm$ 16.0	52.1 $\pm$ 13.2	66.3 $\pm$ 11.2	69.8 $\pm$ 8.5	13.1 $\pm$ 6.3	17.7 $\pm$ 11.4	.202 $\pm$.057	.211 $\pm$.067	61.2 $\pm$ 17.7	63.9 $\pm$ 10.4
	11.8 $\pm$ 1.0†												
t-test	<.5		>.99		<.5		.5-.8		.8		<.5		<.5
Wilcoxon test	.6		.993		<.1		.2		.96		.7		.65

** mean $\pm$ 1 std deviation

† not including sample 28B

Probability
that γ and
control are
different

Table 4 -- Time/sequence correlations, compression tests

Control group				Y group			
σ_{ult} (MPa)	Sequence #	Calendar time, min (from 1/25/82, 0 hrs)	Time out of water, min	σ_{ult} (MPa)	Sequence #	Calendar time, min (from 1/25/82, 0 hrs)	Time out of water
246	2	649	17269	162	1	585	17205
238	4	811	17475	170	3	783	17403
194	6	1937	18557	165	5	930	17550
223	8	2050	18670	164	7	1990	18610
172	10	2128	18748	189	9	2094	18714
231	12	2272	18892	228	11	2239	18839
229	14	2382	19002	119	13	2334	18934
184	16	3401	20021	220	15	3370	19990
128	18	3459	20079	137	17	3428	20048
191	20	3555	20175	104	19	3529	20149
216	23	6442	9787	189	21	6350	9695
201	25	6578	9923	162	22	6412	9757
				141	24	6545	9890
				141	26	6611	9956
linear (vs σ) correlation coefficient, $r^\dagger$	-.42	-.30	-.24	-.27	-.16	-.07	
95% confidence interval of r	[-.78, .20]	[-.72, .32]	[-.71, .38]	[-.68, .28]	[-.62, .39]	[-.55, .47]	
probability of non-correlation, Kendall test	8%	8%	10%	20%	20%	> 25%	

† Pearson's moment r

Figure Captions

1. a) Arrangement of 10 samples in the γ cell and b) rotation schedule of the samples during the γ -irradiation phase.
2. Typical data from the compression tests, these from sample 32A (unirradiated): a) Poisson's ratio ν vs longitudinal strain (ϵ_L). Dashed line is tangent to curve at $\epsilon_L = .1\%$ and defines $\nu(\epsilon_L = .1\%)$, upper arrow, and ν_0 , lower arrow; b) load vs longitudinal strain. The slope of the curve is Young's modulus. The division of the curve into two generally straight portions at $\epsilon_L < .04\%$ and $\epsilon_L > .1\%$ is typical and prompted the use of two parameters, E_1 and E_2 , to characterize the curve; c) load vs volume strain.
3. Compressive strength vs testing sequence for irradiated and unirradiated samples. The straight lines are linear least squares fits to each set of data. Taken separately, the correlation for each group ($r = -0.42$ for the upper line; $r = -0.27$ for the lower line) is not statistically convincing. However, the fact that the correlations have occurred independently forms a statistically convincing probability (0.98) that the correlation exists.
4. Scanning electron micrographs showing typical crack structures in irradiated and unirradiated compression test samples. a) sample 13A, unirradiated, $\sigma^{ult} = 201$ MPa; b) sample 14A, γ -irradiated, $\sigma^{ult} = 141$ MPa. Quartz grains dominate both micrographs. Note that total crack lengths are comparable, despite the strong differences in maximum applied stress. The bar represents 100 μm . The micrographs are backscattered electron images.

Figure 1a

(Looking from outside canister)

Figure 1b

Figure 2a

Figure 2b

Figure 2c

Figure 3

(a)

(b)

Figure 4