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Adoption of a Rapid Test for Determining Aggregate Durability in Portland Cement Concrete

Final Report
to the
Michigan Department of Transportation

Department of Civil and Environmental Engineering
The University of Michigan
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Research and Technology Section
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1. Introduction and Problem Statement

1.1 General

D-cracking is a major distress type in Portland cement concrete pavements caused by repeated cycles of freezing and thawing. This distress occurs mainly when a concrete containing D-cracking susceptible aggregates is exposed to adverse environmental conditions. Therefore, the measurement of an aggregate's resistance to freeze-thaw deterioration is extremely important in cold climatic regions such as Michigan.

The Michigan Department of Transportation (MDOT) currently uses a series of three test methods for determining the frost resistance of aggregates in concrete: Michigan Test Method (MTM) 113[1], which covers procedures for aggregate sampling, testing and moisture conditioning; MTM 114[2], which describes procedures for the preparation of the concrete mixture and test specimens; and MTM 115[3], which describes the testing of the specimens and the criteria for evaluating the durability of the aggregate in concrete. MTM 115 generally conforms to the requirements of AASHTO T161/ASTM C 666[4,5], Procedure B, except that it is more restrictive and detailed. Even though these test methods address some of the inadequacies of the AASHTO/ASTM procedures, drawbacks such as lengthy test duration, and labor-intensive procedures remain. MDOT has desired a simple and rapid test for identifying aggregates that have poor durability without having to cast and test concrete specimens. The Washington Hydraulic Fracture Test (WHFT) was developed during the Strategic Highway Research Program (SHRP) in response to needs like these. The primary reason for this study is to reduce the time required to determine aggregate durability. This report presents the results of a study initiated by MDOT and conducted by a research team from The University of Michigan (U-Mich.), University of Minnesota (U-Minn.) and University of Washington (U-Wash.).

1.2 Background

1.2.1 Occurrence of D-cracking

Numerous research studies have demonstrated that concrete is susceptible to freezing and thawing deterioration when moisture is present. One common indication of deterioration due to freezing and thawing is the appearance of short cracks (typically 20-50 mm) which run approximately parallel to joints or edges of concrete surfaces. These cracks result from the disintegration of coarse aggregates after they have become critically saturated and have been subjected to repeated freeze-thaw cycles. This type of distress is known as D-cracking. As deterioration progresses, these parallel cracks occur farther away from the joints and edges.[6]

The occurrence of the D-Cracking phenomenon has been known to exist since the 1930's[7]. MDOT began performing freeze-thaw testing in 1954[8] in order to detect D-cracking durability problems in aggregates. Over the years, MDOT has modified its test procedures and evaluation criteria in an effort to develop more accurate and representative test results.

The mechanisms that cause D-cracking are not yet completely understood, and efforts are ongoing to establish and clarify the characteristics that make aggregates D-cracking susceptible. The WHFT procedure was developed introducing water rather than mercury into the aggregate pores, and using water pressure to simulate freezing expansion of the water in the pores[9].

1.2.2 Current Test Methods

The most common method used to identify D-cracking susceptible aggregates is AASHTO T161 "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing" (also known as ASTM Test Method C 666). This method has two alternate procedures: Procedure A, which consists of freezing and thawing specimens in water; and Procedure B, which consists of freezing specimens in air and thawing them in water. This test can be conducted with concrete cylinder or prism specimens, although prism specimens are most commonly used.[6] A cycle of freezing and thawing is completed by lowering the specimen temperature from 4°C (40°F) to -17°C (0°F) and raising it back to 4°C (40°F) within a 2 to 5 hour period. The actual time per cycle is usually about four hours per cycle for Procedure A and three hours per cycle for Procedure B. (Procedure A typically requires a longer time period per cycle because of the extra time required to freeze and thaw the water surrounding the concrete specimens). Specimen length change and/or relative dynamic modulus of elasticity (ASTM Test Method C 215)[10] are determined at least every 36 cycles.

This test is run to 300 cycles, or until the specimens fail. Failure is usually considered to be either an expansion greater than 0.1 percent, or a relative dynamic modulus of elasticity of less than 60 percent, although agencies frequently establish their own failure criteria.[11] The Michigan Department of Transportation has established failure criteria for freeze-thaw durability of concretes based on percent expansion of the test specimens. These criteria are described in Table #1.

Table #1. Freeze-Thaw Expansion Limits in Michigan ***(1990 Standard Specifications for Construction-Amended by Special Provisions)***[12]

Allowable Uses	Maximum Expansion per 100 Cycles
Pavement Concrete	0.067
Pavement and Structural Concrete*	0.040
Prestressed Concrete	0.010

* *By special provision for 6AA graded aggregates*

Though most DOT's have had good agreement between field D-cracking susceptibility and AASHTO T161/ASTM C 666 results, there are several drawbacks associated with these procedures. One problem is that the time required to complete the test (typically 14 days of curing plus as many as 40 days or more for freezing and thawing) is significant and the testing itself is labor intensive. (With the current method, the aggregate acceptance procedure takes 3 to 6 months, causing economic setbacks for MDOT, the aggregate producers, and paving contractors). In addition, the equipment used for freezing, thawing, and testing the concrete specimens is costly and often requires periodic maintenance that can be both time-consuming and expensive. Finally, ASTM and AASHTO provide little guidance concerning the preparation of freeze-thaw specimens with respect to aggregate grading, moisture treatment, air content, cement content, and various aspects of curing.

1.3 Problem Statement

The freeze-thaw testing procedure described by AASHTO/ASTM, and modified by MTM is intended to provide a system by which to rate aggregates for resistance to freezing and thawing deterioration. In order to offset the drawbacks of the freeze-thaw procedure, the WHFT procedure may provide a rapid test for initial aggregate acceptance. This project was initiated to verify whether the WHFT method is useful (either as is or in a modified form) as a supplemental procedure for aggregate acceptance testing in Michigan.

2. Research Objectives

The principal objective of this study was to determine if the WHFT can be adopted by MDOT as a part of the acceptance test procedure for evaluating the frost resistance of coarse aggregate sources in Portland cement concrete applications. The research effort also considers any modifications of the Hydraulic Fracture Index (HFI) that would give it more physical significance. A detailed explanation of the HFI is presented in Appendix A. Other goals of the research study included the following:

- Establishing relationships and correlations between the Freeze-Thaw method and the WHFT procedure.
- Calibrating the WHFT and Freeze-Thaw apparatus, and developing a correlation between different laboratories and operators for both WHFT and Freeze-Thaw testing.
- Developing and expanding the principles and theories on which the WHFT procedure is based.
- Refining the apparatus and experimental techniques used to conduct WHFT testing.
- Designing and conducting an experimental program to verify the principles guiding the WHFT method, and modifying the procedure as needed.
- Forming a comprehensive database of pertinent papers and studies that have been conducted relating to Freeze-thaw testing and the WHFT procedure.

3. Project Scope

The scope of the research is summarized as follows:

- Conduct a comprehensive literature review of all subject matter (including past and current research activities) concerning the development and uses of the Washington Hydraulic Fracture Test, and Freeze-Thaw testing.
- Select the required aggregate sources in and around Michigan from a range of dilation values and other qualities which have a direct effect on freeze-thaw durability.
- Correlate WHFT and Freeze-Thaw equipment using the selected control aggregates.
- Determine the variability between the WHFT and Freeze-Thaw test results.
- Determine the WHFT variability between aggregate sources, apparatus, operators and laboratories.
- Investigate the possibility for additional development of the hydraulic fracture concepts by more closely examining the relationships between peak hydraulic pressure and rate of pressure release.
- Modify WHFT apparatus to improve correlations and reduce variability in test results.
- Develop a modified WHFT procedure to be used by MDOT.
- Deliver and install the WHFT apparatus in the MDOT Materials and Testing laboratory.
- Train MDOT personnel to conduct the modified WHFT.

4. Experimental Design

4.1 General

In this research program, keeping the scope in view, the number and type of materials and frequency of tests were selected so that enough data would be available at the end of the program for developing a modified WHFT procedure, as well as the desired correlations. The number of materials selected was sufficient to determine any test variability between materials within a wide range of dilations. Similarly, the same samples were tested under similar conditions by different laboratories to verify the inter-laboratory variability.

All aggregates were collected, graded, and property tested by U-Mich. The samples were then distributed to the various testing sites. Freeze-Thaw testing was conducted at 3 locations, and compared to database values established by MDOT for aggregate samples from the same sources. WHFT testing was performed in 2 laboratories on the same samples tested for Freeze-Thaw resistance. This allowed for correlation of test methods and laboratories (and operators), as well as different aggregate sources.

4.2 Materials Selection

In order to further develop the WHFT and determine its suitability for use in MDOT's aggregate acceptance test program, testing was performed on aggregates that span the range of materials that are likely to be considered for use in MDOT concrete applications. This included various types of natural aggregates and manufactured aggregates. Materials representing a broad range of durabilities, with particular consideration of aggregates in the "marginal" performance band were also included in the program since it is the performance of these materials that tends to be most variable and is most difficult to predict accurately by most current test procedures. MDOT TAC recommended specific aggregate sources that met the above conditions. After careful evaluation, the research team selected aggregates for testing as shown in Table #2.

Table #2. Aggregates Selected for Testing

Aggregate	Pit No.	Remarks
Rockwood (Control)*	58-8	Dolomite, marginal durability, dilation: 0.039%
Marblehead (Control)*	93-1	Limey dolomite & dolomitic limestone, marginal durability, dilation: 0.064%
Drummond (Control)*	17-66	Dolomite, good durability, dilation: 0.001%
Bundy Hill (Control)*	30-35	Gravel, marginal durability, dilation: 0.062%
City Limits	17-20	Gravel, good durability, dilation: 0.001%
Evergreen	52-78	Gravel, poor durability, dilation: 0.261%
Bruce Mine	95-10	Trap rock, good durability, dilation: 0.000%
Celotex	07-36	Gravel, poor durability, dilation: 0.201%
France Stone Silica	93-3	Dolomite, good durability, dilation: 0.006%
Michigan Foundation	82-6	Arenaceous dolomite & limestone, poor durability, dilation: 0.069%
Maybee	58-4	Arenaceous & argillaceous dolomite, marginal durability, dilation: 0.044%
Denniston Farms	58-9	Dolomite, marginal durability, dilation: 0.038%
Recycled I-96 (Brighton, MI)		Recycled, poor durability, dilation: 0.084%

* *The designation "Control" refers to those aggregates used for initial correlation of Freeze-Thaw apparatus and testing facilities.*

The following summary describes the general petrographic composition of the aggregates used in the project.

Rockwood Stone (58-8):

This aggregate is a composite of tan to gray dolomite and limy dolomite quarried from several bedrock ledges. Each ledge has varying amounts of dense to very finely porous to openly porous material. The dense aggregate ranges from 8 to 48 percent while the porous aggregate ranges from 52 to 92 percent. Some of the openly porous particles in this aggregate have been shown to cause freeze-thaw cracks in concrete specimens when vacuum saturated.

Marblehead (93-1):

This aggregate is a composite of gray to tan dolomite and dolomitic limestone quarried from several bedrock ledges. The dense to slightly porous portion accounts for 16 percent of the aggregate. The finely porous aggregate amounts to 33.2 percent and openly porous aggregate makes up 50.8 percent of the total. Due to the high percentage of openly porous material, this source would be expected to record high dilations in freeze-thaw testing.

Drummond (17-66):

This aggregate is a dense white to gray dolomite quarried from a massive uniform bedrock deposit. Due to physical strength and lack of porosity, this source has a record of excellent freeze-thaw durability when vacuum saturated.

Bundy Hill (30-35):

Aggregate from this source is a heterogeneous glacial gravel composed of igneous, metamorphic, and sedimentary rock particles. The deleterious rock types present in the sedimentary rock fraction of this sample as classified by MDOT's freeze-thaw tests are friable sandstone, siltstone, shale, clay-ironstone, and chert. The sedimentary rock fraction also contains a considerable quantity of carbonate rock particles which vary in porosity from dense to openly porous. Some of the openly porous particles have caused freeze-thaw cracks in vacuum saturated concrete specimens.

City Limits (17-20):

This aggregate is a heterogeneous glacial gravel composed of igneous, metamorphic, and sedimentary rocks in the form of dense to slightly porous non-friable sandstone. Occasionally, trace amounts of carbonate rock fragments will be present in some samples. Due to the absence of rock types known to cause freeze-thaw distress, this aggregate has a history of excellent vacuum saturated freeze-thaw durability.

Evergreen (52-78):

This source consists of a heterogeneous glacial gravel of primarily igneous and metamorphic rock particles. Some of these stones are deeply weathered which causes them to be porous and physically weak. The deeply weathered rocks result in this aggregate having a poor vacuum saturated freeze-thaw durability record.

Bruce Mines (95-10):

This aggregate is a dark gray to black gabbroic igneous rock quarried from a massive igneous intrusion. Due to physical strength and lack of porosity this material has a excellent freeze-thaw durability record.

Celotex (7-36):

Glacial gravel from this source consists of a heterogeneous mixture to igneous and metamorphic rock particles. Some of the stones are deeply weathered which results in them being porous and physically weak. The deeply weathered rocks result in this aggregate having a poor vacuum saturated freeze-thaw durability as evidenced by the high dilation value.

France Stone--Silica (93-3):

This aggregate is made up of tan to gray dolomite quarried from several bedrock ledges. The majority of the material varies in porosity from dense to very finely porous, with minor amounts of openly porous particles. This source has a history of good freeze-thaw durability.

Michigan Foundation (82-6):

A detailed petrographic examination of a sample obtained from this source showed that the aggregate was composed of 73 percent highly porous arenaceous dolomite, 12 percent slightly porous argillaceous dolomite, and 15 percent dense argillaceous limestone. The highly porous rock had absorption values ranging from 2.8 to 6.2 percent. A freeze thaw sample obtained from this source recorded a vacuum saturated durability factor of 18 and a 24-hour soak durability factor of 97.

Maybee (58-4):

This aggregate is a combination of arenaceous and argillaceous dolomite with 75 percent of the sample having high porosity values. A freeze-thaw sample from this source had a absorption of 4.2 percent and marginal freeze-thaw dilation values.

Denniston Farms (58-9):

This quarried material is composed of light to dark gray dolomite. An examination revealed the aggregate's composition to be 87 percent openly porous dolomite and 13 percent dense to finely porous dolomite. This is a new aggregate source and, therefore, has little freeze-thaw history.

Of the 13 materials, the first four aggregates, covering a range of dilations were selected as the primary control aggregates; Rockwood Pit No. 58-8, Marblehead Pit No. 93-1, Drummond Pit No. 17-66, and Bundy Hill Pit No. 30-35. These aggregates were chosen from a range of dilations, and were used to calibrate the WHFT apparatus. In addition, these aggregates were used in an inter-laboratory testing program to correlate Freeze-Thaw apparatus at U-Mich., U-Minn., and MDOT.

Special emphasis was given to selecting aggregates exhibiting a wide range of dilations, from low to high, while selecting the control aggregates. One gravel was included as the control aggregate to test the WHFT procedure's ability to evaluate the mix of good and bad particles frequently found in the gravel. All control aggregates used were of MDOT gradation 6 series.

The properties of the aggregate samples used in this project are summarized in Table #3. It should be noted that for two of the control aggregates, Marblehead and Rockwood, the MDOT database values were used for determining mix designs for the batches tested in Freeze-Thaw. The database values for the aggregate properties vary slightly from the values determined for the samples tested in this project. The values reported in Table #3 are those attained from testing of the samples at U-Mich.

Table #3 Aggregate Properties*

Aggregate	Pit #	Bulk Specific Gravity (dry)	% Absorption (24 hr Soak)	% Absorption (Vac. Sat.)	Unit Weight (dry loose, pcf.)
Rockwood *(Control)*	58-8	2.56	3.04	3.73	84.51
Marblehead *(Control)*	93-1	2.47	3.44	4.55	85.83
Drummond *(Control)*	17-66	2.80	0.51	0.53	94.22
Bundy Hill *(Control)*	30-35	2.65	1.25	1.40	100.46
City Limits	17-20	2.68	0.44	0.87	90.21
Evergreen	52-78	2.69	1.99	2.14	96.64
Bruce Mine	95-10	2.81	0.85	0.92	87.14
Celotex	07-36	2.64	2.33	2.66	89.62
France Silica	93-3	2.62	2.39	3.36	87.83
Michigan Foundation	82-6	2.42	4.63	6.58	83.58
Maybee	58-4	2.44	3.79	5.31	82.72
Denniston Farms	58-9	2.57	2.69	3.86	86.17
Recycled I-96		2.35	*N/A*	5.26	84.39

* *All data based on testing conducted at U-Mich.*

The second phase of testing, intended to refine the WHFT procedure, and provide correlating data from freeze-thaw testing involved nine aggregates. The first five aggregates were chosen from a full range of aggregate durability in order to determine the WHFT procedure's ability to predict the full range of durability values. Finally, 3 more aggregates from the marginal dilation ranging from 0.035% to 0.075% were chosen to determine if the WHFT method could accurately distinguish between marginal aggregate durabilities. Additional testing was proposed and conducted on special materials such as deleterious materials (as defined in MTM 117) and recycled concrete aggregate to determine the WHFT's response to special materials.

This test program was conducted using the latest version of the WHFT apparatus and recommended test procedures. The WHFT test program was accompanied by Freeze-Thaw testing of the materials at U-Mich., U-Minn., and MDOT. The purpose of this testing was to develop Freeze-Thaw dilation data for the same samples being tested in the WHFT, and to ensure proper calibration of the project team's Freeze-Thaw machines. Table #4 depicts the testing schedule followed in the study.

Table #4. Material Testing Schedule

Aggregate	Test	U-Mich	U-Minn	U-Wash	MDOT
Rockwood Pit #58-8	Freeze-Thaw	X	X		X
	WHFT		X	X	
Marblehead Pit #93-1	Freeze-Thaw	X	X		X
	WHFT		X	X	
Drummond Pit #17-66	Freeze-Thaw	X	X		X
	WHFT		X	X	
Bundy Hill Pit #30-35	Freeze-Thaw	X	X		X
	WHFT		X	X	
City Limits Pit #17-20	Freeze-Thaw	X			X
	WHFT		X	X	
Evergreen Pit #52-78	Freeze-Thaw	X			X
	WHFT		X	X	
Bruce Mine Pit #95-10	Freeze-Thaw	X			
	WHFT		X	X	
Celotex Pit #07-36	Freeze-Thaw	X			X
	WHFT		X	X	
France Silica Pit #93-3	Freeze-Thaw	X			
	WHFT		X	X	
Mich Found Pit #82-6	Freeze-Thaw	X			
	WHFT		X	X	
Maybee Pit #58-4	Freeze-Thaw	X			
	WHFT		X	X	
Denn. Farms Pit #58-9	Freeze-Thaw	X			
	WHFT		X	X	
Recycled I-96	Freeze-Thaw	X			
	WHFT		X		

4.3 Test Procedures

4.3.1 Freeze-Thaw Testing

Freeze-Thaw tests were conducted on all aggregates using the existing MDOT test procedures. Roughly 2500 lbs. of 6A series material was acquired from various quarries, sieved to required gradations, and distributed to the various test laboratories. This large sample size was obtained to ensure that all testing would be performed on the same sample. The samples were distributed to the various test sites by The U-Mich. research team.

Material properties testing was performed on each aggregate source at the U-Mich. laboratory. Four test samples were prepared from each aggregate. After obtaining the dry unit weight (ASTM C 29)[13], two samples each were soaked under two different conditions, vacuum saturation and 24 hour saturation by soaking in water. The two soaking procedures were used to obtain data on two different saturation conditions. Bulk specific gravity and water absorption (ASTM C 127)[14] of these samples were then determined.

Using the material properties tested under the vacuum saturated condition, 3 batches of concrete mixes were prepared for each aggregate source as per the current MDOT test procedures. The slump (ASTM C 143)[15], air content and unit weight (ASTM C 138)[16], and temperature were noted for each batch. Seven day and 28 day compressive strengths (ASTM C 39)[17] were determined for each batch. For the four control aggregates, nine freeze-thaw beams were prepared and cured in U-Mich. laboratory. From each batch 3 beams each were tested in the three laboratories (MDOT, U-Mich and U-Minn) for Freeze-Thaw dilation. All materials sampling and preparation, Freeze-Thaw testing, and evaluation of results (in terms of % dilation per 100 cycles) were conducted in accordance with MTM's 113, 114, and 115. For the aggregates in the second phase of the study, 3 freeze-thaw beams were made for Freeze-Thaw testing at U-Mich. From time to time three additional beams were prepared to be tested in MDOT lab for comparison purposes. This comparison was done for three of the materials, chosen at random.

4.3.2 Washington Hydraulic Fracture Test

In practice, the WHFT procedure for a sample in the 19 to 25-mm size range, involves obtaining an oven-dry aggregate sample of approximately 200 pieces with a mass of 2,600-3,000 grams and submerging it in a silane solution (Hydrozo's EnviroSeal 40 for example) for one minute. After the silane treatment has been completed, the aggregate is again oven-dried. The sample is tumbled in a rock tumbler for one minute to break up any partially broken pieces, and the exact number of aggregate pieces (retained on the 9.5-mm sieve) and mass are determined for the sample. The sample is then placed in the pressure chamber, and the chamber is bolted shut (taking care that the aggregate is not inadvertently crushed by compression between the chamber lids). The chamber is then turned on edge, so that the pressure isolation/release mount is vertical, and the chamber is filled with water up to the pressure release valve. Care is taken to insure that all of the air is removed from the chamber, as excess air can greatly decrease the rate at which pressure can be released from the chamber. Once the water supply and release valves have been secured, the selected pressure is applied by opening the valve separating the chamber and the compressed nitrogen. The pressure is maintained for five minutes. The top valve is then closed to isolate the chamber from the compressed nitrogen, and the pressure release valve is rapidly opened, thereby quickly releasing the pressure within the chamber. The small amount of water that sprays out upon the pressure release valve opening is replaced by briefly refilling the chamber with water. After one minute of refill time, the chamber is re-pressurized. The pressure is then released after two minutes. An additional eight cycles of two minutes of pressure, pressure release, and no pressure for one minute are applied. At the end of the ten total cycles the pressure chamber is drained and opened. The specimen is oven-dried at 120° C overnight. The following day, the sample is placed in a rock tumbler for one minute. After one minute of tumbling, the sample is separated using 9.5-mm and 4.75-mm sieves. All particles of the sample retained on both sieves are weighed and counted. The material retained on the 9.5-mm sieve is subjected to an additional ten pressurization cycles. The pressurization is repeated for five days, or 50 pressurization cycles for each aggregate sample.

After each day's testing, the ratio of the number of new pieces to the number of original pieces is determined. This ratio is termed the "percent fractures" and is shown in the equation below:

$$FP_i = 100 \times (n4_i + n_i - n_0)/n_0$$

where FP_i is the percent fractures after "i" pressurization cycles,

$n4_i$ is the number of pieces passing the 9.5-mm sieve but retained on the #4 sieve after "i" pressurization cycles,

n_i is the number of pieces retained on the 9.5-mm sieve after "i" pressurization cycles, and

n_0 is the number of pieces initially tested.

The percent fractures is used to calculate an index value called the Hydraulic Fracture Index (HFI), which is the number of cycles necessary to produce 5 percent fracturing. It is determined by one of the following methods, depending upon the percent fracturing after 50 cycles of pressurization.

If 5 percent fracturing is achieved in 50 or fewer cycles, the HFI is calculated as a linear interpolation of the number of cycles that produced 5 percent fractures:

$$HFI = A + 5 \times [(5 - FP_A)/(FP_B - FP_A)]$$

where A is the number of cycles just prior to achieving 5 percent fracturing,

FP_A is the percentage of fracturing just prior to achieving 5 percent fracturing, and

FP_B is the percentage of fracturing just after achieving 5 percent fracturing.

If 5 percent fracturing had not occurred by the end of 50 pressurization cycles, the HFI would have been calculated by linearly extrapolating a line that passed through the points at zero cycles and 50 cycles out to 5 percent fracturing. The equation that gives the HFI for this case is

$$HFI = 50 \times (5/FP_{50})$$

where: FP_{50} = percent fracturing after 50 pressurization cycles.

5. ANALYSIS OF DATA

5.1 Correlation with MTM 115

The analyses described in this section were performed using only those data that were obtained from tests performed using 7930 kPa (1150 psi) chamber pressure and 620 kPa (90 psi) actuator pressure, which was the test configuration finally adopted, as described in Appendix B of this report. A summary of the test data and relevant test parameters for each test is included in Appendix E. Many other test runs were performed using the "control" aggregates and different chamber pressures, chamber sizes, pressure release systems (manual vs. pneumatic actuator), actuator pressures, chamber linings (neoprene or none), etc. The results of these tests are included in Appendix F, but were not included in the analyses described in this report. Furthermore, they should not be used for direct comparisons with the data presented in Appendix E because they generally represent the results of "nonstandard" test conditions.

5.1.1 Selection of Hydraulic Fracture Test Result for Correlations

As discussed in meetings with the MDOT technical advisory group (TAG), there are some problems inherent with the Hydraulic Fracture Index as it is currently defined (see Appendix B). The current index is intended to represent the number of cycles of hydraulic test pressurization required to produce 5 percent computed fractures in the test sample based on linear interpolation or extrapolation. However, the equation "blows up" under some circumstances, yielding either undefined values (division by zero) or near-infinitely large values (dividing by very small values). These characteristics and the open-ended nature of the HFI scale make it very difficult to correlate test results with freeze-thaw dilation test results, which typically have a very finite range. In practice, the potential for exceedingly large HFI values for aggregates with very small amounts of fracturing has been addressed by limiting the maximum HFI value to the designation ">500." However, correlations are further complicated by the fact that the very compact range of acceptable dilations (less than 0.067% or 0.040% per 100 cycles of freezing and thawing, per MDOT 1990 Standard Specifications and 1990 Standard Special Provisions, respectively) must be tied to a very large portion of the HFI range, while the broader range of unacceptable dilations (anything greater than 0.067% or 0.040% per 100 cycles) is tied to a relatively small portion of the HFI range (0 to 50). It is possible that this latter difficulty could have been mitigated by correlating dilation with some logarithmic function of HFI, but the portion of the project team responsible for this portion of the analysis elected to pursue correlations with more direct outputs of the test: particle fractures and mass loss.

To further simplify analyses, it was decided to do all correlations and model development with data obtained from tests of the large aggregate size fraction (19 to 25 mm) because larger particle sizes are generally more strongly associated with dilation and durability problems. The results of tests of the smaller particles could then be used to either validate any models or relationships.

Initial modeling efforts focused on trying to develop broad-based multivariate linear and nonlinear models of freeze-thaw dilation as a function of particle counts on the 9.5-mm (3/8-in) sieve, mass passing the 9.5-mm (3/8-in) sieve, total mass loss, hydraulic fracture index, HFI, total computed percent fractures, mass retained on the 4.75-mm (#4) sieve and other variables. It was hoped that a single model could be developed to apply to all aggregate types tested. Unfortunately, it soon became apparent that no single- or multivariate model could be easily developed to accurately model dilation using the test data collected to date. The best correlations with dilation were obtained using particle counts on the 9.75-mm (3/8-in) sieve and various measures of mass loss; even these provided very low r-squared values, however.

During this initial analysis, it became clear that the most rapid progress would result from analyses that included as few variables as possible. With this in mind, the data were split into pools of "carbonate-based" and "gravel/minerock" categories; the classification or category assigned to each aggregate source (on the basis of petrographic examination by MDOT personnel) is listed in Table 3. The subsections below discuss the results of analyses of the data within each of these categories. Although these analyses did not produce numerical models of dilation as a function of mass loss or percent fractures, they did reveal some strong relationships between dilation and mass loss and computed particle fracture, which are discussed below. These relationships were further strengthened (i.e., test result variability was reduced) when the particle counts used to comprise a single "test" was increased to 600 or more, as suggested by the findings of the original apparatus development test program. For tests of 19 to 25-mm (3/4-in to 1-in) aggregates, this required combining the particle counts and mass losses from 3 replicate tests of approximately 200 particles each to provide a single test result based on approximately 600 particles.

Due to the lengthy development and refinement of the test apparatus and procedures, there are three or fewer total runs with the proper test configuration for many test cells (i.e., for many combinations of operator, aggregate source, test apparatus, etc.), resulting in only 1 "test" for these cells, some of which represent fewer than 600 particles. However, as many as 14 replicate runs were performed for some test cells, resulting in literally hundreds of possible combinations of "tests" comprised of triplicate runs (e.g., 1, 2 and 3; 1, 2 and 4, ... 1, 3 and 4, 1, 3 and 5, etc.). While it was recognized during the analysis that the consideration of all possible combinations of test results from a pool of test runs includes a high degree of redundancy, it was considered more important to consider all such combinations to get a better feel for the potential range and variability of test results that might be derived from a random sample of aggregates in a test.

5.1.2 Analysis of Correlation with Gravel/Minerock Sources

Five gravel/minerock sources were considered in this test program: Bundy Hill (30-35), City Limits (17-20), Evergreen (52-78), Celotex (07-20) and Bruce Mines (95-10). Petrographic examinations by MDOT personnel indicate that Evergreen (52-78) and Celotex (07-20) are composed of igneous and metamorphic materials, while Bundy Hill (30-35) and City Limits (17-20) contain these particles and sedimentary particles as well. Bruce Mines (95-10) is a strong, low-porosity, gabbroic, igneous rock. All of the gravel sources except City Limits (17-20) were noted as containing physically weak, openly porous particles. For example, Bundy Hill (30-35) was found to contain only 37.1% igneous/metamorphic particles, 55.6% carbonate particles, 4.6% chert and 2.7% sandstone, siltstone, shale and clay ironstone. The City Limits (17-20) sample was of much different composition than the other three gravels, containing 84.3% igneous/metamorphic materials, 14.7% sandstone and 1% siltstone.

Freeze-thaw tests performed at the Universities of Michigan and Minnesota found that all of the gravel sources except City Limits (17-20) would fail to meet the requirements of MDOT 1990 Standard Special Provisions, with dilations exceeding 0.04% per 100 cycles. Celotex (07-20) and Evergreen (52-78) would also fail to meet the requirements of MDOT 1990 Standard Specifications, with dilations exceeding 0.067% per 100 cycles. City Limits (17-20) and Bruce Mines (95-10) produced practically no dilation and were considered to have excellent freeze-thaw durability.

Figures 1 and 2 present plots of the percent fracture after 50 cycles of pressurization versus dilation for the hydraulic fracture tests performed on the 19- to 25-mm (3/4- to 1-in) materials at the Universities of Minnesota and Washington, respectively; the dilation data in each figure are the results of freeze-thaw tests (MTM 115) performed at the University of Michigan. Each plotted point represents the average of all hydraulic fracture tests performed when three or fewer tests were considered in the analysis; otherwise, each point represents the average of all possible combinations of runs taken three-at-a-time for the runs within any given test cell. Tables 5 and 6 provide some details concerning the data presented in these figures. Similarly, tables 7 and 8 provide details concerning the data presented in figures 3 and 4, which are plots of mass loss versus dilation for the hydraulic fracture tests performed at Minnesota and Washington, respectively.

Figure 1 indicates a very strong correlation between computed fracture rate and dilation, with only City Limits (17-20) as an outlier characterized by high fracture rates and low dilation. As described previously, MDOT petrographic examinations found that City Limits (17-20) contains large amounts of porous, nonfriable sandstone. Tests of dense dolomite samples "spiked" with 25% by weight of various deleterious and soft materials (conducted at the University of Washington and described in section 5.3.2 of this report) found that, when sandstone was the "spiking" agent, an average of 2.2% fracture rate and 0.625% mass loss were computed. Assuming that the only material in these blends subject to significant fracture was the sandstone, these rates might correspond to 8.8% fracture and 2.50% mass loss for 100% sandstone. These fractures and this mass loss might attributed to either handling of the sandstone (sieving and tumbling of the aggregates between pressurization cycles) or failure in response to internal pore pressures (MDOT reported a 34.6% unconfined aggregate freeze-thaw loss with the same "spiked" blend that was tested at Washington). In either case, it is clear that a relatively small quantity of sandstone can produce large rates of fracture and/or mass loss without producing much dilation in concrete specimens. This suggests that the hydraulic fracture test may suggest rejection of otherwise durable sandstone-bearing aggregate sources, depending upon the rejection criteria selected and the sandstone content of aggregate.

On this basis, it is possible that Bundy Hill (30-35) should be excluded from these analyses as well, even though it contained only one-tenth the quantity of sandstone found in City Limits (17-20). MDOT unconfined aggregate freeze-thaw tests of Bundy Hill (30-35) samples produced a 48.7% mass loss for the "soft" (sandstone) particles (see Table 9). In addition,

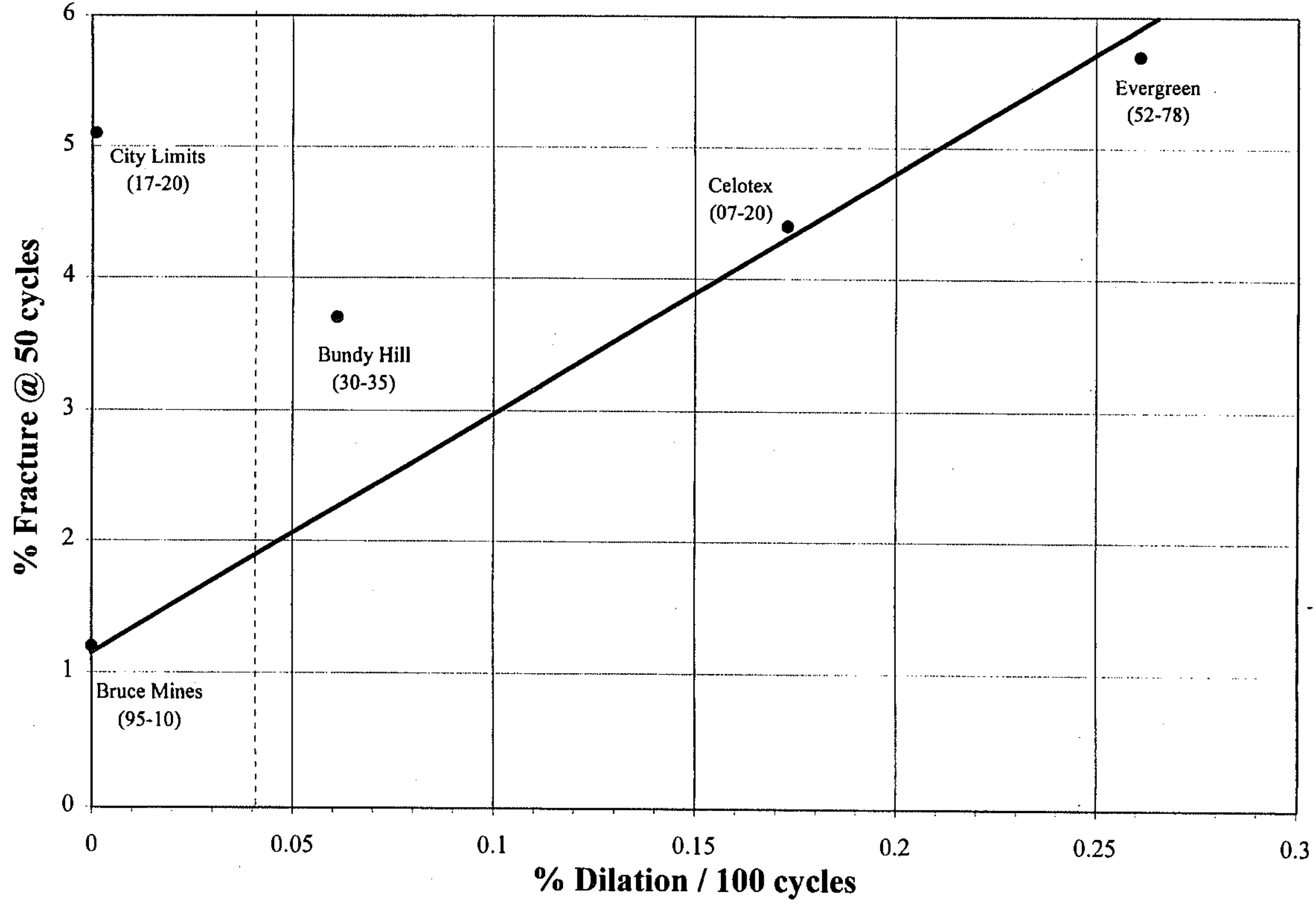

Figure #1. % Fracture vs Dilation, 19 - 25-mm Gravel/Minerock Aggregates
(U-Minn WHFT Data)

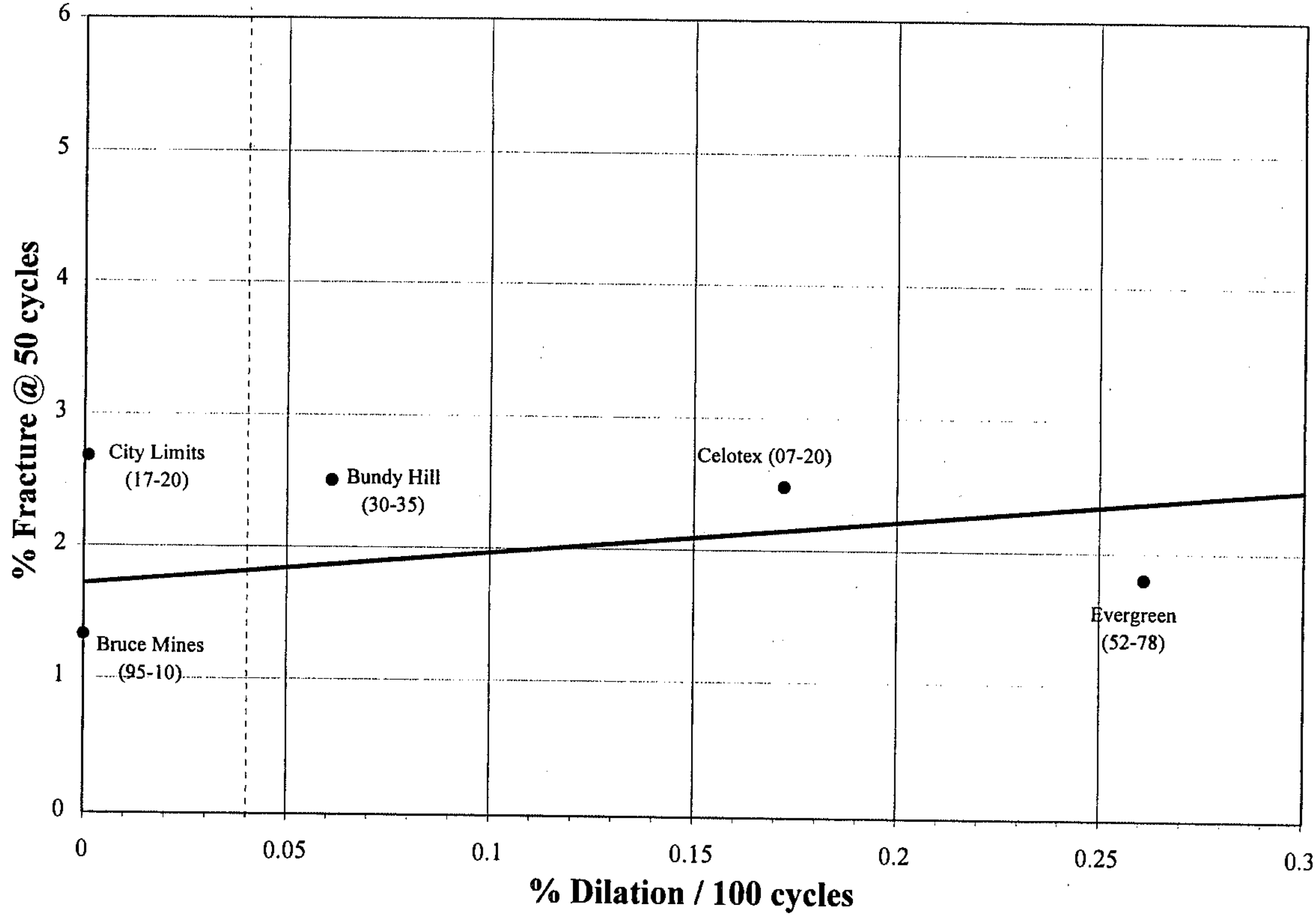

Figure #2. % Fracture vs Dilation, 19-25-mm Gravel/Minerock Aggregates
(U-Wash WHFT Data)

Table #5. % Fracture and Dilation Data, 19 - 25-mm Gravel/Minerock Aggregates
(U-Minn WHFT Data)

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Number of Tests Conducted	Number of 3-Way Combinations n	% Fracture @ 50 cycles (Average of (n) Tests)	Range of % Fracture @ 50 Cycles
Bundy Hill (30-35)	0.061	10	120	3.7	1.6 - 7.3
Bruce Mines (95-10)	0.000	3	1	1.2	----
Celotex (07-20)	0.173	3	1	4.4	----
City Limits (17-20)	0.001	3	1	5.1	----
Evergreen (52-78)	0.261	3	1	5.7	----

Table #6. % Fracture and Dilation Data, 19 - 25-mm Gravel/Minerock Aggregates (U-Wash WHFT Data)

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Number of Tests Conducted	Number of 3-Way Combinations n	% Fracture @ 50 cycles (Average of (n) Tests)	Range of % Fracture @ 50 Cycles
Bundy Hill (30-35)	0.061	14	364	2.5	0.4 - 5.0
Bruce Mines (95-10)	0.000	4	4	1.3	0.6 - 1.8
Celotex (07-20)	0.173	4	4	2.5	2.0 - 2.6
City Limits (17-20)	0.001	4	4	2.7	2.0 - 2.3
Evergreen (52-78)	0.261	4	4	1.8	1.3 - 2.3

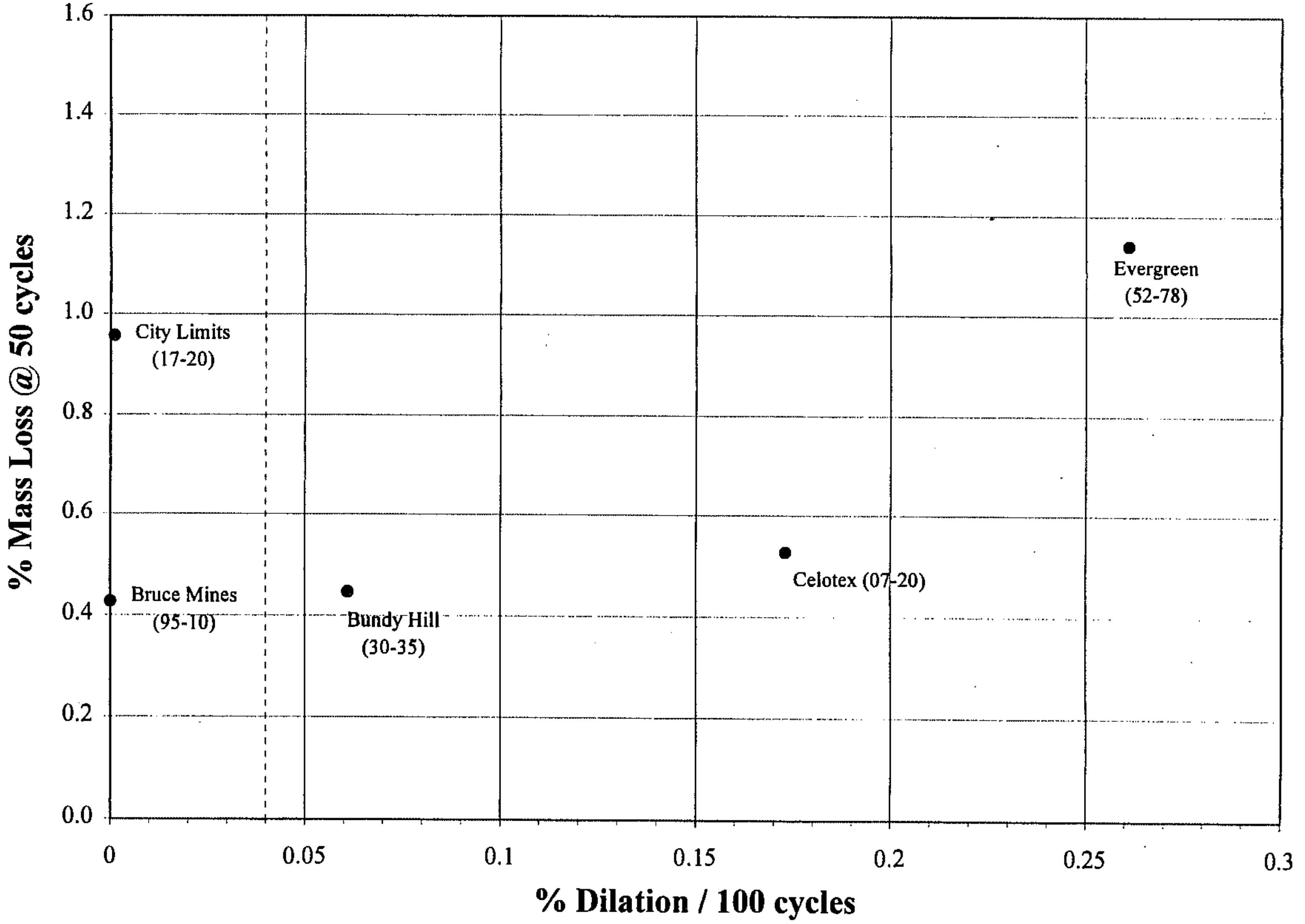

Figure #3. % Mass Loss vs Dilation, 19 - 25-mm Gravel/Minerock Aggregates
(U-Minn WHFT Data)

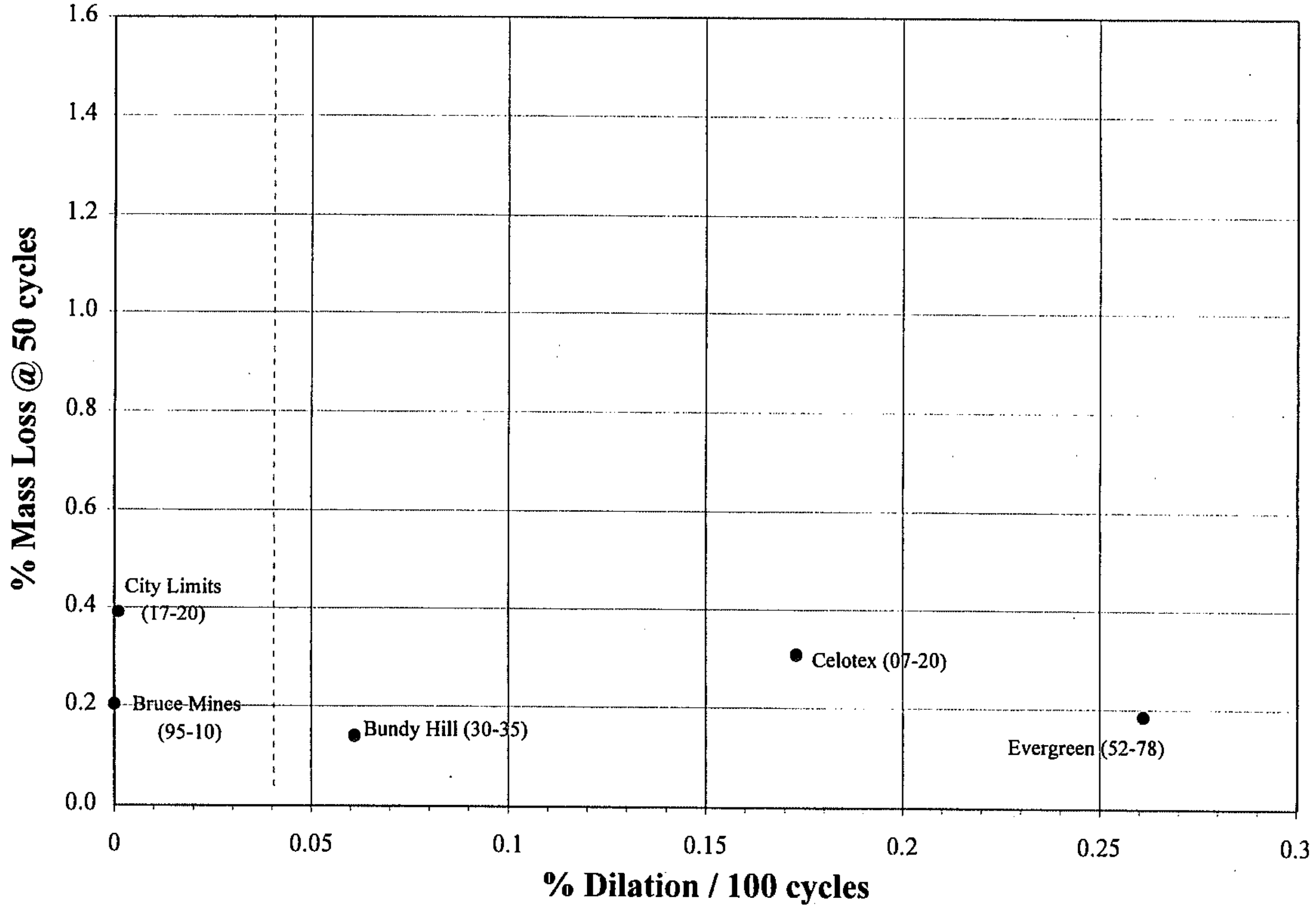

Figure #4. % Mass Loss vs Dilation, 19-25-mm Gravel/Minerock Aggregates
(U-Wash WHFT Data)

Table #7. % Mass Loss and Dilation Data, 19 - 25-mm Gravel/Minerock Aggregates
(U-Minn WHFT Data)

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Number of Tests Conducted	Number of 3-Way Combinations n	% Mass Loss @ 50 cycles (Average of (n) Tests)	Range of % Mass Loss @ 50 Cycles
Bundy Hill (30-35)	0.061	10	120	0.45	0.24 - 1.18
Bruce Mines (95-10)	0.000	3	1	0.43	----
Celotex (07-20)	0.173	3	1	0.53	----
City Limits (17-20)	0.001	3	1	0.96	----
Evergreen (52-78)	0.261	2	1	1.14	----

Table #8. % Mass Loss and Dilation Data, 19 - 25-mm Gravel/Minerock Aggregates
(U-Wash WHFT Data)

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Number of Tests Conducted	Number of 3-Way Combinations n	% Mass Loss @ 50 cycles (Average of (n) Tests)	Range of % Mass Loss @ 50 Cycles
Bundy Hill (30-35)	0.061	14	364	0.14	0.06 - 0.24
Bruce Mines (95-10)	0.000	4	4	0.20	0.14 - 0.23
Celotex (07-20)	0.173	4	4	0.31	0.26 - 0.36
City Limits (17-20)	0.001	4	4	0.39	0.36 - 0.42
Evergreen (52-78)	0.261	4	4	0.19	0.16 - 0.2

Table #9. Unconfined Freeze-Thaw Tests for Selected Aggregate Sources

Source	Sample No.	Particle Type	Mass Loss (%)
France Stone (93-03)	92A-3436	Dense Carbonate Particles	1.3
		Porous Carbonate Particles	0.6
Bundy Hill (30-35)	92A-3438	Igneous/Metamorphic Particles	0.2
		Porous Carbonate Particles	2.0
		MDOT "Soft" Particles	48.7
		Chert Particles	11.8
Rockwood (58-08)	92A-3439	Dense Carbonate Particles	1.4
		Porous Carbonate Particles	0.6
		Porous Carbonate Particles	6.5
Marblehead (93-01)	94A-3008	Dense Limestone Particles	0.5
		Porous Dolomite/Limestone Particles	1.1
Celotex (07-36)	94A-3002	Dense Igneous/Metamorphic Particles	4.0
		Porous Igenous/Metamorphic Particles	16.4

Note: Unconfined freeze-thaw tests were conducted by MDOT on these aggregates following a 24 hour soak period without vacuum saturation. The samples were subjected to 300 cycles of freezing and thawing at a rate of 8 cycles per day, according to ASTM C666 Method B. Unconfined frost resistance was measured by loss of mass by screening after completion of the tests.

Bundy Hill (30-35) contains nearly 5% chert, which is highly active in producing concrete dilation and popouts but does not break in the hydraulic fracture test (see section 5.3.2). The two effects seem to be somewhat offsetting, producing more test result variability than for most sources, but an average that lies near the "best-fit" line.

Considering Figure 1 and discarding the City Limits (17-20) data, a best-fit line through the remaining data points suggests that aggregates with average fracture rates greater than 2.6% correspond to dilations greater than 0.067% per 100 cycles and should be rejected to provide compliance with MDOT 1990 Standard Specifications. Similarly, aggregates with average fracture rates greater than 2.2% correspond to dilations greater than about 0.04% per 100 cycles and should be rejected to provide compliance with MDOT 1990 Standard Special Provisions. A band of test result variability exists about this best-fit line, so any fracture rate acceptance criteria should be selected with consideration of the possibility of obtaining nonrepresentative samples. Some guidance on the selection of this criteria can be based on the confidence interval surrounding the Bundy Hill (30-35) fracture data, which has a lower limit of 1.35% for 90% confidence. For example, constructing a line through this point and parallel to the "best-fit" line suggests that aggregates with average fracture rates greater than 1.2% should be rejected to comply with the 1990 Standard Special Provisions; a slightly higher value (e.g., 1.5%) might be less likely to result in the rejection of durable aggregates.

University of Washington gravel fracture data are presented in Figure 2 and Table 6. Consideration of all of these data (excluding City Limits (17-20) for the reasons discussed above) still indicates a slight trend of increasing fracture with increasing dilation, with a best-fit line through the remaining data points suggesting that aggregates with average fracture rates greater than 1.85% correspond to dilations greater than 0.04% per 100 cycles and should be rejected for compliance with the MDOT's 1990 Standard Special Provisions. The 1.5% criteria suggested above would provide a greater degree of confidence while rejecting all known nondurable aggregate test results from Washington.

A comparison of Figures 1 and 2, which represent the results of tests of the same gravel/minerock materials performed at different labs and by different operators, suggests that test results were not consistently repeatable between labs. A closer examination of these data suggest that the test results obtained from each lab exhibited the same general trends, but that the Washington results occurred within a more compressed scale, thereby producing a flatter slope for the best-fit line through the data points. It is hypothesized that much of the difference in test results may be attributable to differences in the test apparatus release rates at the two universities (i.e., Minnesota release rates averaged 40,000 psi/sec while Washington release rates averaged 50,000 psi/sec for the same actuator pressure; see Figure 5), which have been correlated inversely with particle fracture rates. This difference between lab results and apparatus release rates is discussed in more detail in sections 5.2.4 (Variability Between Labs), 6.1 (Conclusions) and 6.2 (Recommendations).

Figures 3 and 4 suggest no clear relationships between mass loss and dilation for the gravel samples, although the high mass loss without significant dilation associated with the City Limits (17-20) source (due to the sandstone content) is clearly indicated.

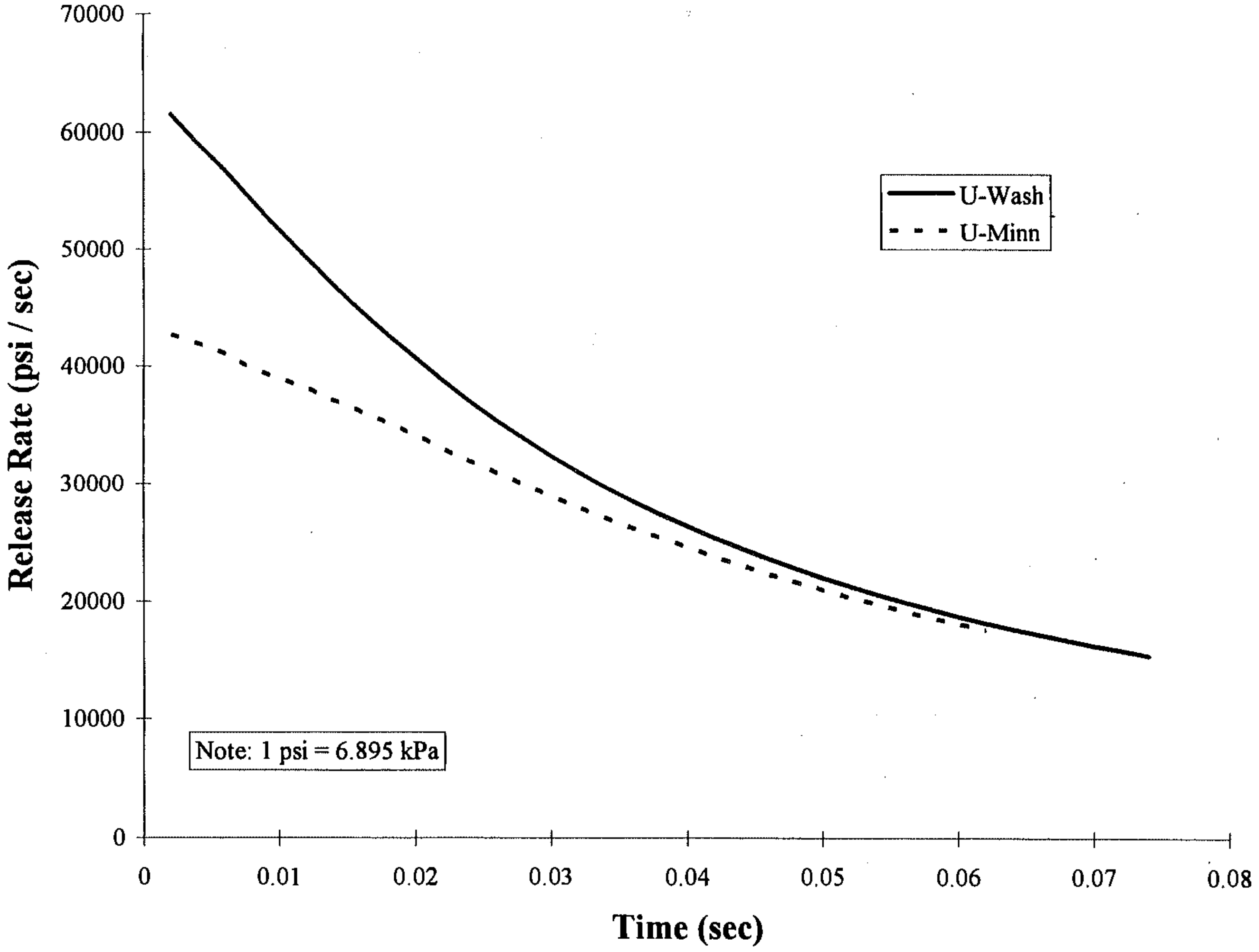

Figure #5. Release Rate Data for Chamber Pressure of 1150 psi and Solenoid Pressure of 90 psi

Other highway agencies have adopted more simple quick-screen techniques for assessing the freeze-thaw resistance of gravel aggregates. For example, the Minnesota DOT currently rejects gravels for use as coarse aggregate in PCC mix designs if the carbonate content of the gravel exceeds 30% by weight of the bulk aggregate. This screen successfully distinguishes between the relatively poor durability of the high-carbonate Bundy Hill source(30-35) and the excellent durability of low-carbonate City Limits source (17-20). Relative quantities of carbonate in the other sources considered here could be evaluated with respect to this (or other) criterion to determine whether carbonate content might provide a strong indicator of freeze-thaw durability for Michigan gravel sources.

Particle density and porosity are also often considered indicators of concrete aggregate freeze-thaw durability. Figures 6 and 7 present graphs of specific gravity and absorption capacity, respectively, versus dilation for the five gravel sources considered in this project; Tables 10 and 11 summarize the data presented in Figures 6 and 7, respectively. Figure 6 indicates that there is no apparent relationship between specific gravity and dilation for the aggregates tested. However, Figure 7 indicates a strong correlation between absorption capacity and dilation, with absorption capacities greater than 1.3% being associated with unacceptably high dilations. Additional tests should be performed on a wider range of aggregate sources to verify the usefulness of an absorption-based screen for gravel aggregate sources.

It must be emphasized that this study was not set up to properly study any of the "quick-screen" tests mentioned in the previous two paragraphs and the authors do not necessarily advocate their adoption. These data are presented and briefly discussed only to document observations that may or may not bear additional consideration. It is also worth noting that the correlation of absorption capacity and carbonate content with freeze-thaw dilation may not correlate with field performance.

5.1.3 Analysis of Correlation with Carbonate Sources

Seven carbonate sources were considered in this test program: Rockwood (58-08), Marblehead (93-01), Drummond (17-66), France Stone (93-03) (Silica), Michigan Foundation (82-06), Maybee (58-04) and Dennison Farms (58-09). Petrographic examinations by MDOT personnel indicate that Drummond (17-66) and Maybee (58-04) are pure dolomites, while the remaining sources are dolomitic limestones (see Table 3). All of the carbonate sources considered here except for Drummond (17-66) contain varying quantities of porous carbonate particles (Drummond (17-66) is stated to be composed only of dense material).

Freeze-thaw tests performed at the Universities of Michigan and Minnesota found that, of the carbonate sources, only the Michigan Foundation source (82-06) produced dilations exceeding the MDOT 1990 Standard Specification acceptance limit of 0.067% per 100 cycles; only the Drummond and France Stone sources (17-66 and 93-03, respectively) produced dilations below the 0.04% per 100 cycle limit set forth in the MDOT 1990 Standard Special Provisions.

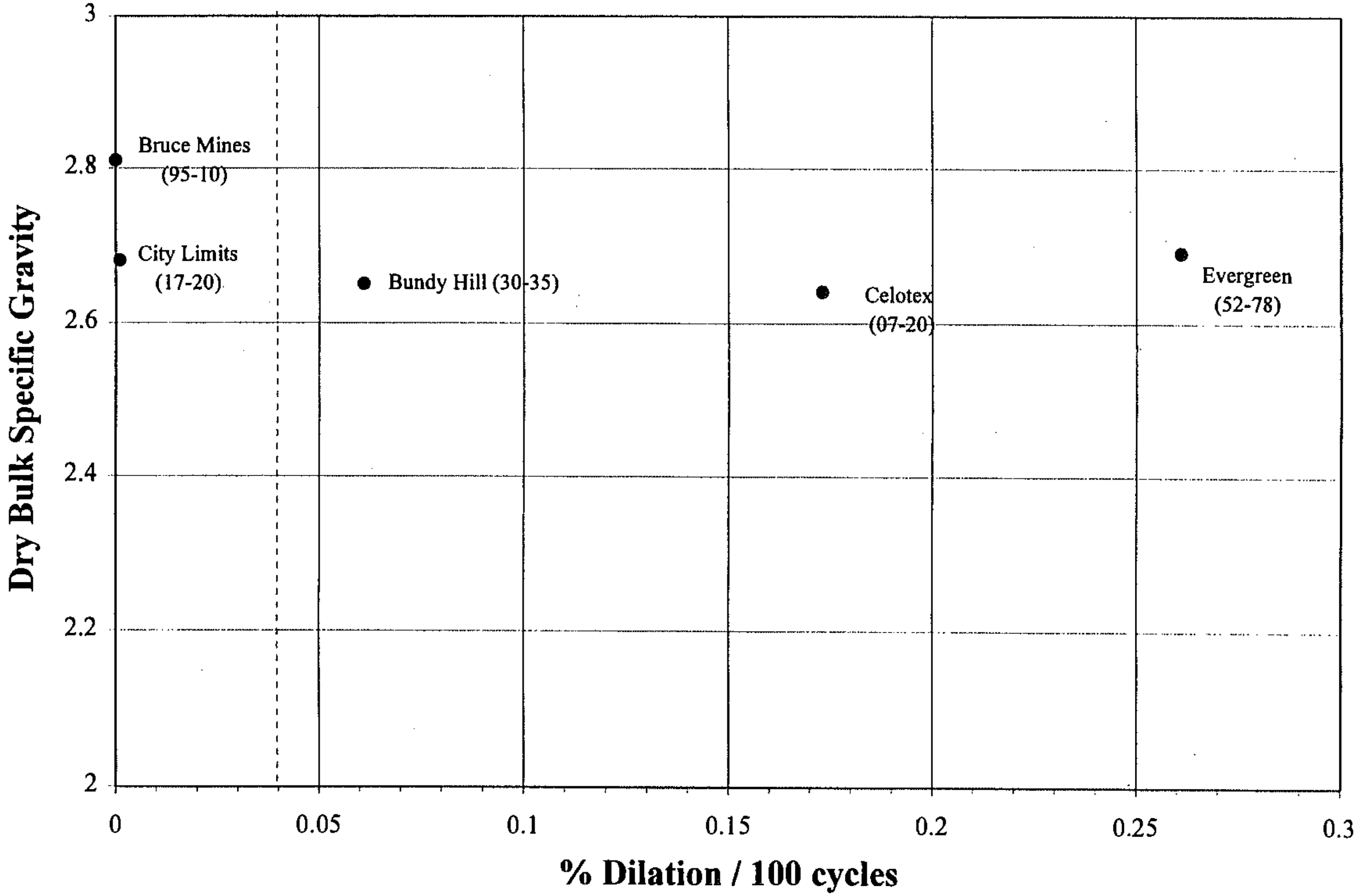

Figure #6. Dry Bulk Specific Gravity vs Dilation for Gravel/Minerock Aggregate Sources

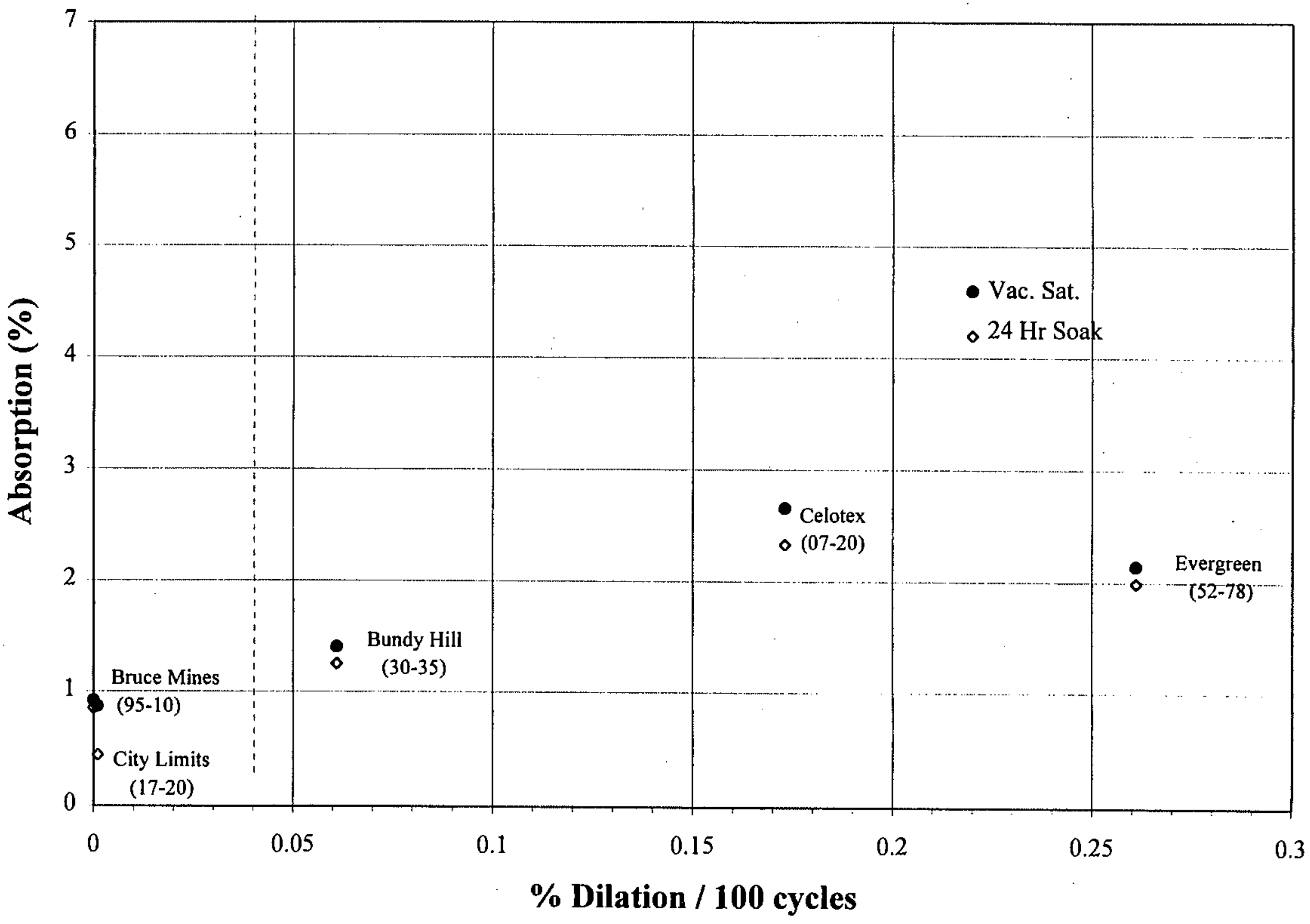

Figure #7. Absorption vs Dilation for Gravel/Minerock Aggregate Sources

Table #10. Dilation and Dry Bulk Specific Gravity Data for Gravel/Minerock Aggregate Sources

Source	Freeze-thaw Dilation, % per 100 cycles (U Mich Data)	Dry Bulk Specific Gravity (U Mich Data)
Bundy Hill (30-35)	0.061	2.65
Bruce Mines (95-10)	0.000	2.81
Celotex (07-20)	0.173	2.64
City Limits (17-20)	0.001	2.68
Evergreen (52-78)	0.261	2.69

Table #11. Dilation and Absorption Data for Gravel/Minerock Aggregate Sources

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Absorption (%)	
		24 Hour Soak (U-Mich Data)	Vacuum Saturation (U-Mich Data)
Bundy Hill (30-35)	0.061	1.25	1.40
Bruce Mines (95-10)	0.000	0.85	0.92
Celotex (07-20)	0.173	2.33	2.66
City Limits (17-20)	0.001	0.44	0.87
Evergreen (52-78)	0.261	1.99	2.14

Figures 8 and 9 present plots of the percent fracture after 50 cycles of pressurization versus dilation for the tests performed on the 19- to 25-mm (3/4- to 1-in) materials at the Universities of Minnesota and Washington, respectively. Each plotted point represents the average of all tests performed when three or fewer tests were considered in the analysis; otherwise, each point represents the average of all possible combinations of three for the tests that were considered. Tables 12 and 13 provide some details concerning the data presented in these figures. Similarly, Tables 14 and 15 provide details concerning the data presented in Figures 10 and 11, which are plots of mass loss versus dilation for the hydraulic fracture tests performed at Minnesota and Washington, respectively.

At first glance, there does not seem to be a strong correlation between particle fractures and dilation (see Figures 8 and 9), although mass loss and dilation appear to be directly related (see Figures 10 and 11). These figures suggest two possible ways to use the hydraulic test results to obtain the same screening that would be obtained using MTM 115 in combination with the 1990 Standard Specifications and Standard Special Provisions. One approach is to reject all carbonate aggregate sources with computed fracture rates exceeding 2% or mass losses greater than 0.5%. For the Minnesota test data (presented in Figures 8 and 10), this would eliminate all of the sources with unacceptable dilation except for Marblehead (93-01), which (according to MDOT petrographers) appears to fail in the transition zone between aggregate and mortar and might not be expected to fail a test that does not simulate this failure mechanism. These rejection criteria do not produce the desired results for the Washington data (see Figures 9 and 11). The second approach is to ignore aggregate particle fracture and reject all carbonate sources with mass losses exceeding 0.2%. Considering the data produced at either University, this approach results in the rejection of <u>all</u> of the aggregate that fail MTM 115, as well as France Stone-Silica (93-03), which historically has exhibited acceptable dilation. The rejection of a few "good" sources is probably acceptable for a "screening test," provided that MTM 115 is used to verify rejection.

Another use of the hydraulic fracture test as a slightly less severe "screening test" would be to accept all carbonate aggregates with mass losses less than 0.2%, reject those with mass losses exceeding 0.5%, and test all those falling between these criteria using MTM 115. For the results of this study, this approach would have resulted in the rejection of the materials that produce the worst dilation, the acceptance of the best aggregate source, and freeze-thaw testing of the marginal sources (and one low-dilation source).

It is worth noting that other states have adopted simple screening test criteria for carbonate freeze-thaw durability that provide results as good as those described above. For example, the Minnesota DOT currently requires that carbonate aggregates have an absorption capacity (24-hour soak) of less than 1.75%. Figure 12 provides a plot of absorption versus dilation for the Michigan carbonate-based aggregates included in this study; this data is summarized in Table 16. This figure shows that the 1.75% absorption criteria would result in the rejection of all carbonate aggregate sources tested except for Drummond (17-66), which is clearly a durable aggregate source. The use of a much higher rejection threshold (4%, assuming absorption based on vacuum saturation, or 3%, assuming absorption based on a 24-hour soak) would result in the rejection of only the three sources that failed to meet dilation criteria for

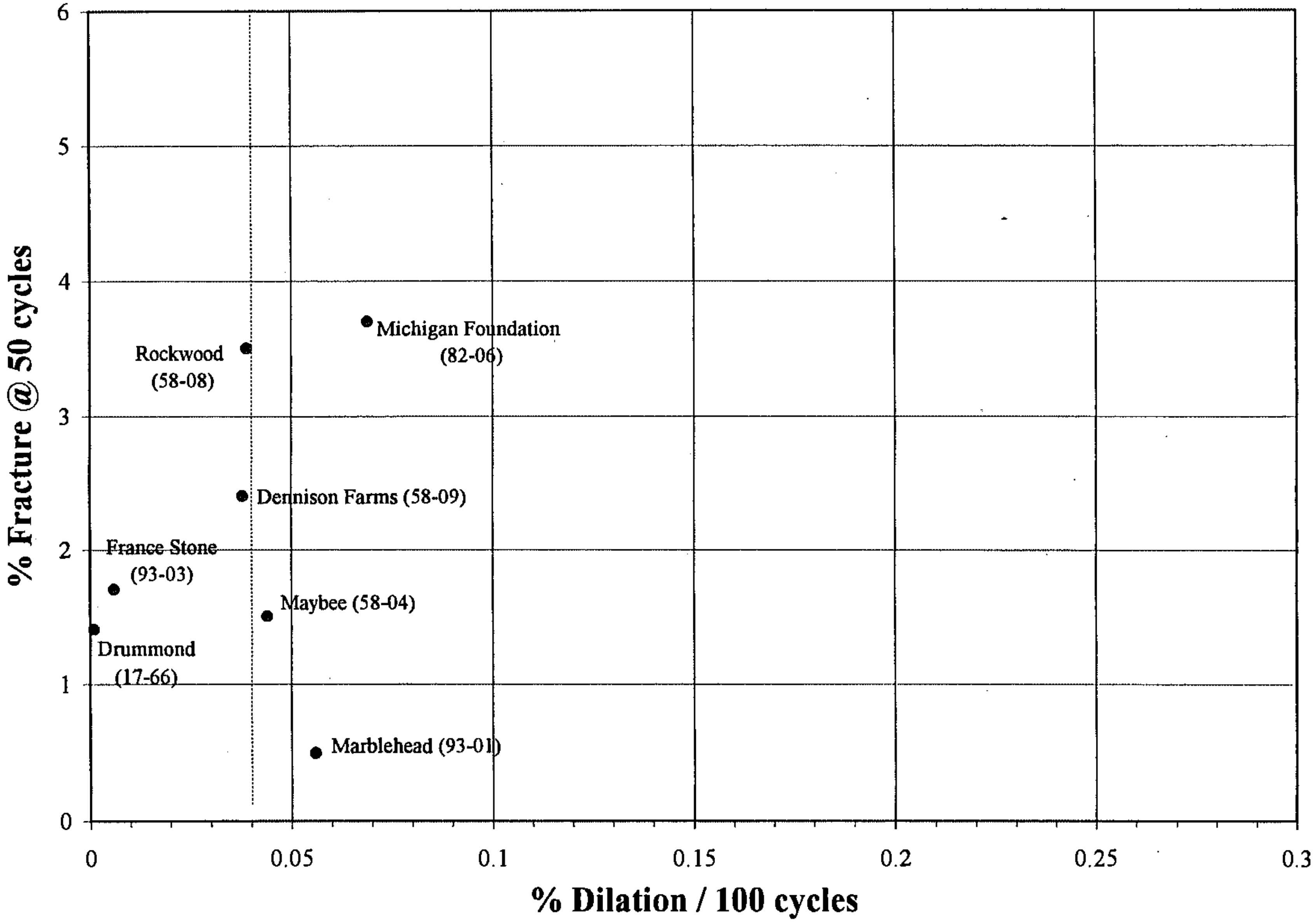

Figure #8. % Fracture vs Dilation, 19-25-mm Carbonate Aggregates
(U-Minn WHFT Data)

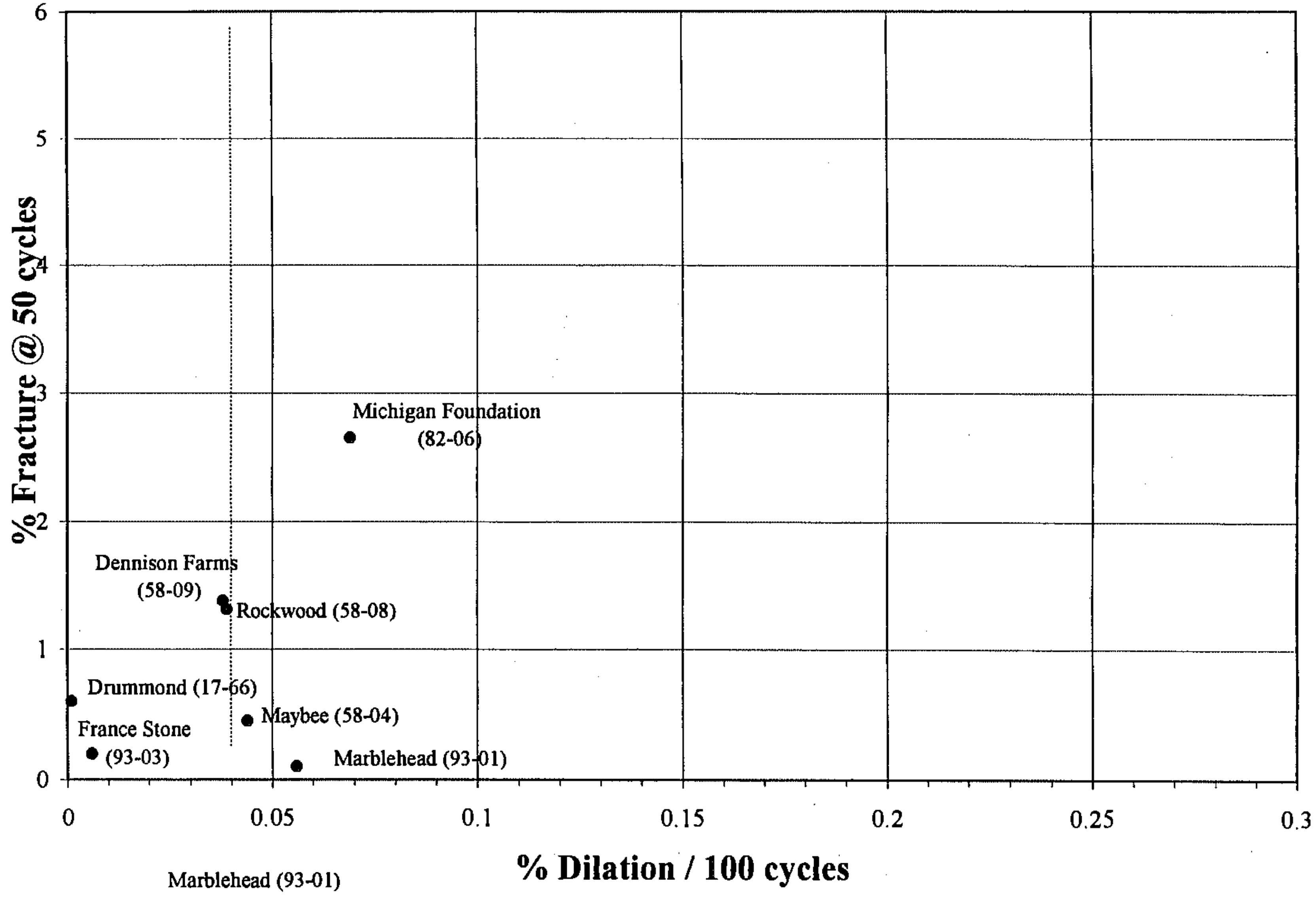

Figure #9. % Fracture vs Dilation, 19-25-mm Carbonate Aggregates
(U-Wash WHFT Data)

Table #12. % Fracture and Dilation Data, 19 - 25-mm Carbonate Aggregates (U-Minn WHFT Data)

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Number of Tests Conducted	Number of 3-Way Combinations n	% Fracture @ 50 cycles (Average of (n) Tests)	Range of % Fracture @ 50 Cycles
Dennison Farms (58-09)	0.038	3	1	2.4	----
Drummond (17-66)	0.001	1	1	1.4	----
France Stone (93-03)	0.006	3	1	1.7	----
Marblehead (93-01)	0.056	2	1	0.5	----
Michigan Foundation (82-06)	0.069	3	1	3.7	----
Maybee (58-04)	0.044	3	1	1.5	----
Rockwood (58-08)	0.039	1	1	3.5	----

Table #13. % Fracture and Dilation Data, 19 - 25-mm Carbonate Aggregates (U-Wash WHFT Data)

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Number of Tests Conducted	Number of 3-Way Combinations n	% Fracture @ 50 cycles (Average of (n) Tests)	Range of % Fracture @ 50 Cycles
Dennison Farms (58-09)	0.038	4	4	1.4	1.3 - 1.5
Drummond (17-66)	0.001	2	1	0.6	----
France Stone (93-03)	0.006	4	4	0.2	0.1 - 0.3
Marblehead (93-01)	0.056	2	1	0.1	----
Michigan Foundation (82-06)	0.069	4	4	2.7	2.3 - 2.9
Maybee (58-04)	0.044	4	4	0.5	0.3 - 0.6
Rockwood (58-08)	0.039	10	120	1.3	0.5 - 2.1

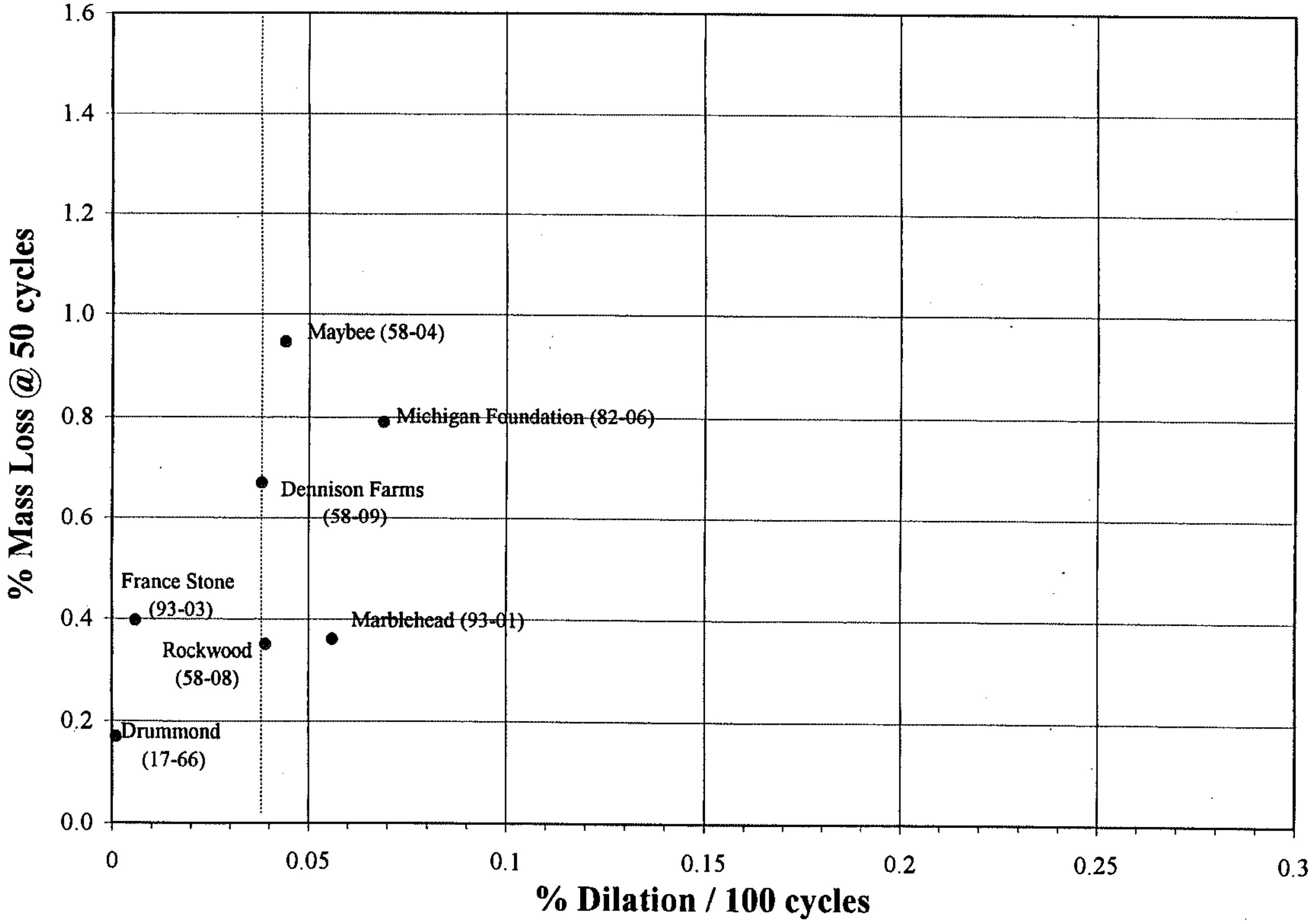

Figure #10. % Mass Loss vs Dilation, 19-25-mm Carbonate Aggregates
(U-Minn WHFT Data)

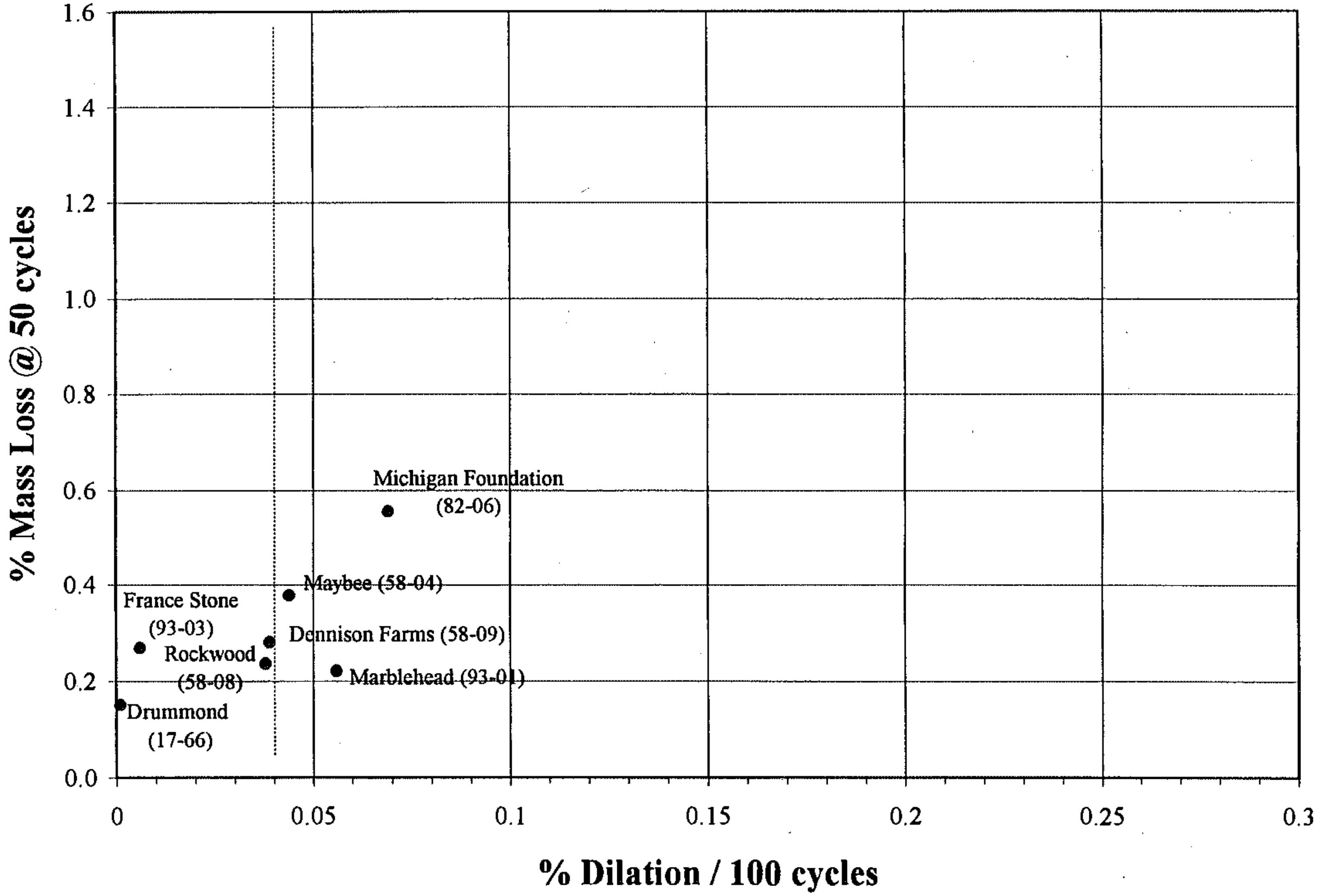

Figure #11. Mass Loss vs Dilation, 19-25-mm Carbonate Aggregates
(U-Wash WHFT Data)

Table #14. % Mass Loss and Dilation Data, 19 - 25-mm Carbonate Aggregates (U-Minn WHFT Data)

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Number of Tests Conducted	Number of 3-Way Combinations n	% Mass Loss @ 50 cycles (Average of (n) Tests)	Range of % Mass Loss @ 50 Cycles
Dennison Farms (58-09)	0.038	3	1	0.67	----
Drummond (17-66)	0.001	2	1	0.17	----
France Stone (93-03)	0.006	3	1	0.40	----
Marblehead (93-01)	0.056	2	1	0.36	----
Michigan Foundation (82-06)	0.069	3	1	0.79	----
Maybee (58-04)	0.044	3	1	0.95	----
Rockwood (58-08)	0.039	1	1	0.35	----

Table #15. % Mass Loss and Dilation Data, 19 - 25mm Carbonate Aggregates
(U-Wash WHFT Data)

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Number of Tests Conducted	Number of 3-Way Combinations n	% Mass Loss @ 50 cycles (Average of (n) Tests)	Range of % Mass Loss @ 50 Cycles
Dennison Farms (58-09)	0.038	4	4	0.24	0.21 - 0.25
Drummond (17-66)	0.001	2	1	0.15	----
France Stone (93-03)	0.006	4	4	0.27	0.25 - 0.28
Marblehead (93-01)	0.056	2	1	0.22	----
Michigan Foundation (82-06)	0.069	4	4	0.56	0.49 - 0.60
Maybee (58-04)	0.044	4	4	0.38	0.37 - 0.38
Rockwood (58-08)	0.039	10	120	0.28	0.20 - 0.50

MDOT 1990 Standard Special Provisions (Michigan Foundation (82-06), Marblehead (93-01) and Maybee (58-04)). Similarly, Figure 13 illustrates the relationship between the bulk specific gravity and MTM 115 dilation of carbonate aggregates; this data is summarized in Table 17. In this case, a specific gravity criterion of 2.5 would successfully discriminate between aggregates that meet or fail the dilation criterion set forth in MDOT 1990 Standard Special Provisions.

The use of simplistic screening criteria such as absorption capacity and specific gravity probably offer a reasonably accurate screen for the freeze-thaw durability of many carbonate aggregate sources. However, they fail to simulate freeze-thaw mechanisms and do not directly consider all aggregate properties that influence freeze-thaw durability (e.g., particle strength, pore size distribution, sorptive characteristics, etc.) As a result, correlations between measures of absorption, specific gravity and freeze-thaw durability sometimes fail to identify nondurable carbonate sources and sometimes reject durable sources (Snyder and Koubaa, 1996). MDOT may benefit from further research concerning the use of such simple tests as preliminary screening predictors of freeze-thaw durability, but previous research studies have rejected their use as final acceptance/rejection tools.

5.2 Analysis of Test Variability

5.2.1 Variability Between Operators

Table 18 presents a summary of the average and standard deviation of the computed fracture and mass loss for tests of Bundy Hill (30-35) 19- to 25-mm (3/4- to 1-in) aggregate performed at the University of Minnesota by three different operators. It can be shown that there is no statistically significant difference between the mean values of the tests performed by each operator. While the mean test values are fairly close, a major part of the reason why the values are not considered significantly different is because the test results obtained by operators 1 and 2 is high.

One source of the large computed standard deviations for these two operators is the relatively small number of tests performed (only three for operator 1 and two for operator 2). All three operators were well-trained, and their personal techniques are not considered a source of significant variability. It is more likely that most of the variability can be attributed to the composition of the Bundy Hill (30-35) aggregate source, which included many varieties of minerals that are known to perform poorly in the hydraulic fracture test. In fact, one of the operators noted that, in one test, only one aggregate particle fractured, but that it did so repeatedly during the test program. This resulted in a high fracture count where only one particle was actually deteriorating. Thus, it appears that the Bundy Hill (30-35) source was, in hindsight, a poor choice for evaluating test repeatability between operators. This experience also provided one of the first clear indications of the need for an improved technique for determining the number of aggregate particles responsible for the many particle fragments that can be produced during the test.

The issue of operator variability was reconsidered during further development of the hydraulic fracture apparatus (funded by the University of Minnesota Graduate School). Some of the results of these tests are summarized in Table 19 (Hietpas, 1996). These test data are quite

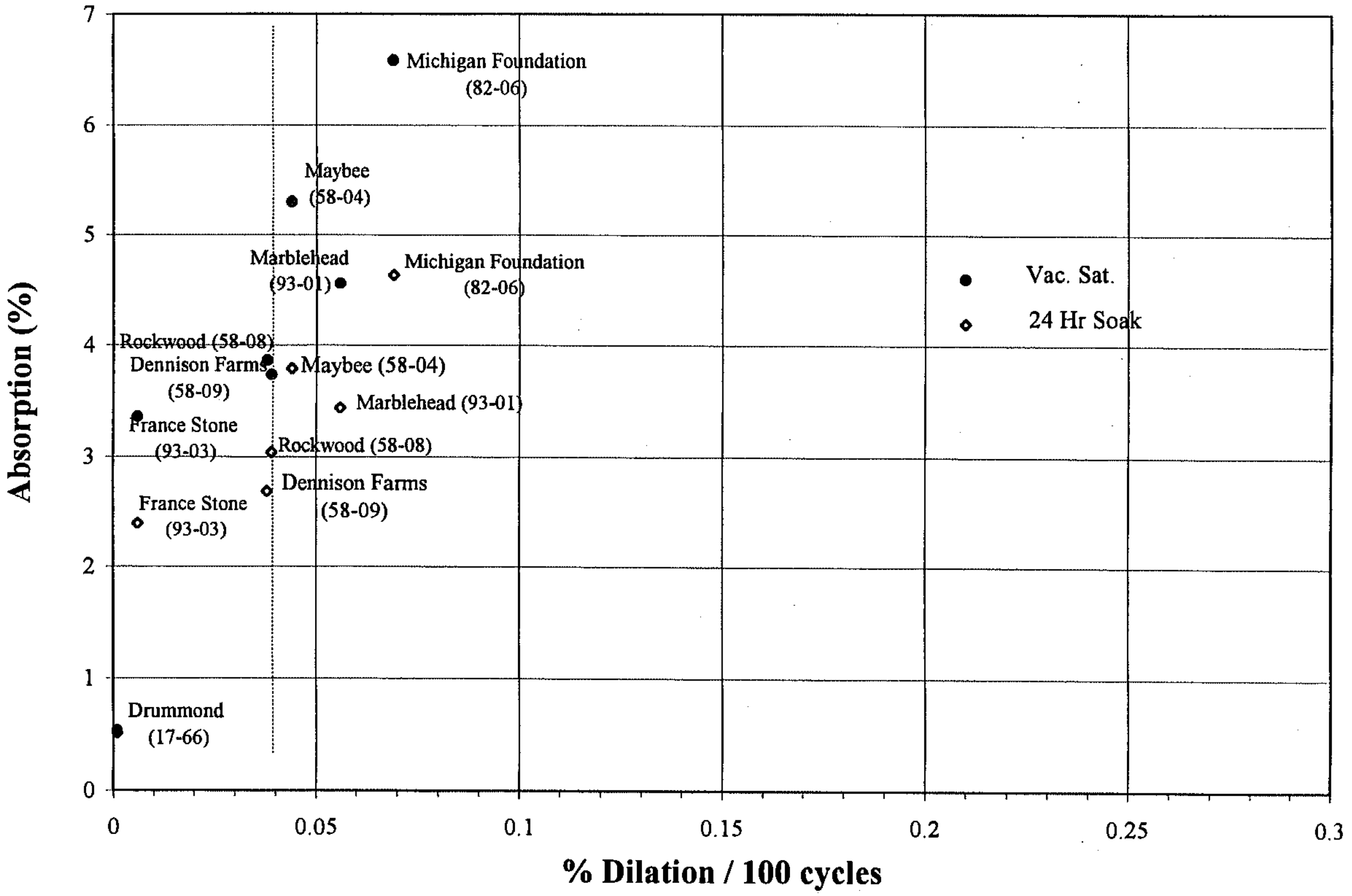

Figure #12. Absorption vs Dilation for Carbonate Aggregate Sources

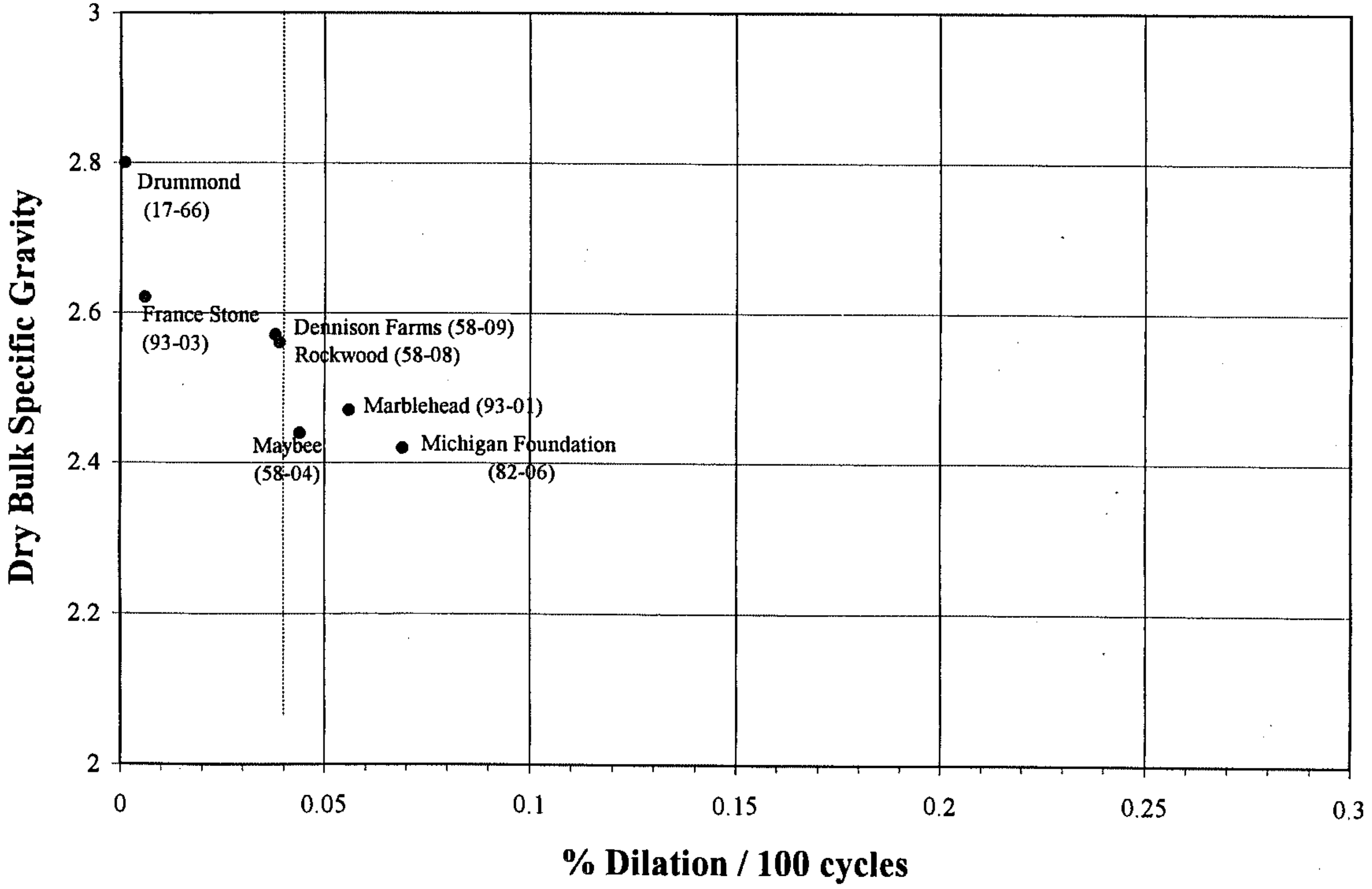

Figure #13. Dry Bulk Specific Gravity vs Dilation for Carbonate Aggregate Sources

Table #16. Dilation and Absorption Data for Carbonate Aggregate Sources

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Absorption (%) 24 Hour Soak (U-Mich Data)	Absorption (%) Vacuum Saturation (U-Mich Data)
Dennison Farms (58-09)	0.038	2.69	3.86
Drummond (17-66)	0.001	0.51	0.53
France Stone (93-03)	0.006	2.39	3.36
Marblehead (93-01)	0.056	3.44	4.55
Michigan Foundation (82-06)	0.069	4.63	6.58
Maybee (58-04)	0.044	3.79	5.3
Rockwood (58-08)	0.039	3.04	3.73

Table #17. Dilation and Dry Bulk Specific Gravity Data for Carbonate Aggregate Sources

Source	Freeze-thaw Dilation, % per 100 cycles (U-Mich Data)	Dry Bulk Specific Gravity (U-Mich Data)
Dennison Farms (58-09)	0.038	2.57
Drummond (17-66)	0.001	2.80
France Stone (93-03)	0.006	2.62
Marblehead (93-01)	0.056	2.47
Michigan Foundation (82-06)	0.069	2.42
Maybee (58-04)	0.044	2.44
Rockwood (58-08)	0.039	2.56

Table #18. Comparison of Operator Effects on % Fracture Data and % Mass Loss Data for 19 - 25-mm Bundy Hill (U-Minn Data)

Operator / Test #	% Fracturing at 50 Cycles 1	2	3	% Mass Loss at 50 Cycles 1	2	3
1	2.20	6.90	2.80	0.28	0.38	0.27
2	0.80	2.10	3.20	0.87	0.25	0.27
3	10.80		4.10	1.18		0.51
4			1.90			0.24
5			3.60			0.43
Average	4.60	4.50	3.12	0.78	0.32	0.34
St. Dev	5.41	3.39	0.83	0.46	0.09	0.12

Table #19. Results of Additional Tests to Evaluate Between-Operator Variability

	% Fracture @ 50 Cycles			
	Operator #1		Operator #2	
Source	Test #1	Test #2	Test #3	Test #4
City Limits (17-20)	3.0	6.8	2.8	1.8
Rockwood (58-08)	1.1	0.8	4.2	1.1
Bundy Hill (30-35)	0.0	0.3	0.6	0.3
Minnesota Limestone #1	0.8	1.9	0.4	1.2
Minnesota Limestone #2	0.0	0.0	0.0	0.0
Minnesota Limestone #3	1.2	0.0	1.9	0.8
Minnesota Gravel #1	0.4	0.0	0.4	0.0

limited, but they indicate that variations in the test results obtained during the MDOT-funded portion of this study were probably due mainly to variances in equipment "calibration" (i.e., pressure release rates) and inherent material variability, and not to differences in test operators. Although the test procedure represented by these results is slightly modified from the procedure used for the MDOT study that is the principal subject of this report (new apparatus calibration techniques have been developed, as have techniques for estimating the number of fractured aggregate particles), it is believed that these results provide a better indication of the repeatability of tests between operators than the results obtained during the MDOT-funded study.

5.2.2 Variability Within Sources

Tables 20 and 21 present summaries of the average and standard deviation of the computed fracture percentage and the mass loss, respectively, for each of the sources tested at each of the two labs. All operators are combined at any given lab because, based on section 5.2.1, it is not believed that variability between operators is a significant effect. The data presented in these two tables represent the average and standard deviation of the individual test runs for each source, not the statistics for the set of all possible combinations of test runs taken three-at-a time.

Analyses of the data presented in these tables show that, while the absolute values of the test results generally become more variable as the magnitude of the result increases (e.g., standard deviation of percent fracture and mass loss increases as percent fracture and mass loss increase themselves), the relative variation remains fairly constant with an average coefficient of variation of about 0.5 (or 50%) for both percent fracture and mass loss as measured at either test lab. Furthermore, analyses showed that these conclusions were generally true for all types of aggregate tested, regardless of the results of dilation tests. This suggests that the variability of the hydraulic fracture test is relatively insensitive to aggregate type or durability.

5.2.3 Variability Between Apparati

Tests were performed at the University of Minnesota to measure the variability in hydraulic fracture test results obtained by the same operator using two different apparati. All variables except test apparati (i.e., operator, lab location, chamber pressure, solenoid actuator pressure, particle count per test and aggregate source) were held constant. The aggregate source used for these tests was Bundy Hill (30-35), and the test equipment were the U-Minn and MDOT apparati. Three samples were tested using each piece of equipment; the test results are summarized in Table 22.

The amount of fracturing observed in each test sample was similar except for one sample, which produced a computed fracture count that was 5 to 10 times higher than that of any other sample; however, the operator noted that all of the observed fracturing in this case was due to the repeated fracture and disintegration of a single piece of aggregate, resulting in an unrealistically high computed fracture count. Even when this anomalous test result is included in the analyses, hypothesis testing suggests that the mean difference in particle fracture rates between the two pieces of equipment was not significant. The data were subjected to a two-tailed t-test, which

Table #20. % Fracture at 50 Cycles for all sources, 19 - 25-mm

Source	U-Minn Average of (n) Tests	Standard Deviation	n	U-Wash Average of (n) Tests	Standard Deviation	n
Bundy Hill (30-35)	3.84	2.95	10	2.52	2.11	14
Bruce Mines (95-10)	1.23	0.60	3	1.33	1.68	4
Celotex (07-20)	4.44	1.27	3	2.48	1.55	4
City Limits (17-20)	5.10	1.46	3	2.68	1.64	4
Dennison Farms (58-09)	2.43	1.84	3	1.38	0.30	4
Drummond (17-66)	1.40	----	1	0.60	0.14	2
Evergreen (52-78)	5.73	0.81	3	1.80	1.41	4
France Stone (93-03)	1.73	1.33	3	0.20	0.16	4
Michigan Foundation (82-06)	3.73	0.78	3	2.65	0.84	4
Marblehead (93-01)	0.50	0.42	2	0.10	0.14	2
Maybee (58-04)	1.47	0.76	3	0.45	0.33	4
Rockwood (58-08)	3.50	----	1	1.31	0.73	10

Table #21. % Mass Loss at 50 Cycles for all sources, 19 - 25-mm

	U-Minn			U-Wash		
Source	Average of (n) Tests	Standard Deviation	n	Average of (n) Tests	Standard Deviation	n
Bundy Hill (30-35)	0.47	0.31	10	0.15	0.05	14
Bruce Mines (95-10)	0.55	0.14	3	0.20	0.12	4
Celotex (07-20)	0.53	0.07	3	0.31	0.16	4
City Limits (17-20)	0.96	0.28	3	0.39	0.10	4
Dennison Farms (58-09)	0.67	0.49	3	0.24	0.05	4
Drummond (17-66)	0.17	----	1	0.15	0.01	2
Evergreen (52-78)	1.15	0.10	3	0.19	0.06	4
France Stone (93-03)	0.40	0.08	3	0.27	0.04	4
Michigan Foundation (82-06)	0.79	0.15	3	0.56	0.14	4
Marblehead (93-01)	0.34	0.03	2	0.22	0.04	2
Maybee (58-04)	0.95	0.38	3	0.38	0.02	4
Rockwood (58-08)	0.34	----	1	0.28	0.09	10

Table #22. Variability Between Apparati for Bundy Hill 19-25-m

Appartus	Initial Particle Count	% Fracture @ 50 Cycles	% Mass Loss @ 50 Cycles
U-Minn	179	2.2	0.3
U-Minn	180	0.8	0.9
U-Minn	180	10.8	1.2
MDOT	180	0.0	0.2
MDOT	180	1.7	0.2
MDOT	180	0.6	0.6

suggested that, at the level $\alpha = 0.1$, there is not enough evidence to suggest that the two means are significantly different. Similar conclusions could be drawn concerning the mass loss data obtained from the same tests using the two different hydraulic fracture test apparati.

While the two apparati discussed above did not yield significantly different test results when used by the same operator, other study conclusions suggest that other pairs of apparati might easily yield very different test results, as is discussed in the next subsection.

5.2.4 Variability Between Labs (Varying Operator and Apparatus)

Tables 20 and 21 can also be used to determine the variability in hydraulic fracture test results between labs. Even though it appears fairly apparent that there is some systematic difference between the results obtained at the two laboratories, hypothesis testing was performed on measurements of percent fracture obtained for each aggregate source tested at both labs to determine whether the apparent differences are statistically significant. For these studies, the null hypothesis is selected as: $\mu_{UMN} = \mu_{UW}$;the alternative hypothesis is: $\mu_{UMN} \neq \mu_{UW}$. A two-tailed t-test was selected and the assumption was made that the population standard deviations at both labs were equivalent. Insufficient tests were performed at one of the labs to allow an analysis of the Rockwood (58-08) and Drummond (17-66) data.

For Bruce Mines (95-10), Bundy Hill (30-35) and Marblehead (93-01), the null hypothesis <u>cannot</u> be rejected at the $\alpha = 0.1$ level, indicating that the difference between mean values between the labs for these aggregate sources would not be considered strong.

For Celotex (07-20), Michigan Foundation (82-06) and Maybee (58-04), the null hypothesis <u>is rejected</u> at the <u>$\alpha = 0.1$</u> level, indicating a strong probability of a true difference in mean values obtained at the two labs. Assuming that the samples at each lab are representative, it is likely that this difference in results can be attributed to some other difference between the two lab operations (e.g., equipment, operators, environment, etc.).

For France and City Limits (17-20), the null hypothesis <u>is rejected</u> at the <u>$\alpha = 0.05$</u> level, indicating a very strong probability of a true difference in mean values obtained at the two labs. The possible sources of this difference are as described above.

For Evergreen (52-78), the null hypothesis <u>is rejected</u> at the <u>$\alpha = 0.025$</u> level, an extremely strong indicator of a true difference in mean values obtained at the two labs. The possible sources of this difference are as described above.

This apparent variability between results obtained using different test apparatus was studied further in 1996 under a grant provided by the Graduate School of the U-Minn (Hietpas, 1996). Additional tests were performed on samples obtained from the Evergreen (52-78) aggregate source using the Minnesota, Washington and MDOT hydraulic fracture equipment. During these tests, all known test variables were held constant (i.e., particle count, solenoid actuator pressure, chamber pressure, etc.), but release rate was monitored and the incidence of particle fracture was recorded as usual. A graphical presentation of some of the results of this study is presented in Figure 14, which shows a strong relationship between pressure release rate and the incidence of particle fracture, with particle fracture rates decreasing with increasing pressure release rate (at least within the range of pressure releases considered here). This discovery also helps to explain the differences in fracture rates obtained at the Universities of Washington and Minnesota throughout this research study, because standardized test procedures yielded pressure release rates of approximately 42,000 psi/sec (290 kPa/sec) in Minnesota (yielding higher incidences of fracture) and 50,000 - 60,000 psi/sec (340 - 410 kPa/sec) in Washington (resulting in lower incidences of fracture).

Another inference that can be drawn from this and other unpublished data is that pressure release rates can vary broadly between apparati (presumably due to differences in valve stiffness and minor plumbing variations), even when all known input variables are held constant. A corollary to this inference would be that it should be possible to match release rates between various apparati by varying the input variables. This hypothesis was tested in 1996 under a grant from the Graduate School at the University of Minnesota (Hietpas, 1996); a sampling of results from this study is included in Figure 15. This figure shows that the Minnesota apparatus was "calibrated" to produce a release rate profile that was practically identical to that of the Washington apparatus by increasing the U-Minn solenoid actuator pressure from 620 kPa to 1000 kPa (90 psi to 145 psi).

The effectiveness of this calibration procedure was then tested by preparing additional samples of the Evergreen (52-78) aggregate source for testing at the Universities of Minnesota and Washington. A representative sampling of the results of this test program is presented in Table 23, which indicates that the "calibrated" Minnesota apparatus produced fracture rates that were very comparable to those obtained at Washington, while the same apparatus run using the lower solenoid actuator pressure and release rate produced much higher rates of aggregate fracture.

These findings strongly suggest that test protocols can be (and should be) modified for each individual test apparatus to produce some accepted and standardized pressure release curve. The results described above suggest that this "calibration" would enhance test repeatability between various apparati and labs. One way to achieve this matching of pressure release rates is to modify the solenoid actuator pressure (as was done in the Minnesota study). Other "calibration" techniques (i.e., plumbing modifications, etc.) may also be possible, but may require much more work.

5.2.5 Effect of Particle Count on Rates of Fracture and Mass Loss

Figures 16 through 27 present graphs of particle count (i.e., number of particles in the chamber during any single test run) versus percent fracture for each of the aggregate sources tested. There are no clear universal trends, although the test results of certain aggregate types seem sensitive to the number of particles in the chamber during testing.

For example, within the gravel/minerock group, Evergreen (52-78) and Celotex (07-20) (which contain some openly-porous particles) appear to produce more fracturing when particle

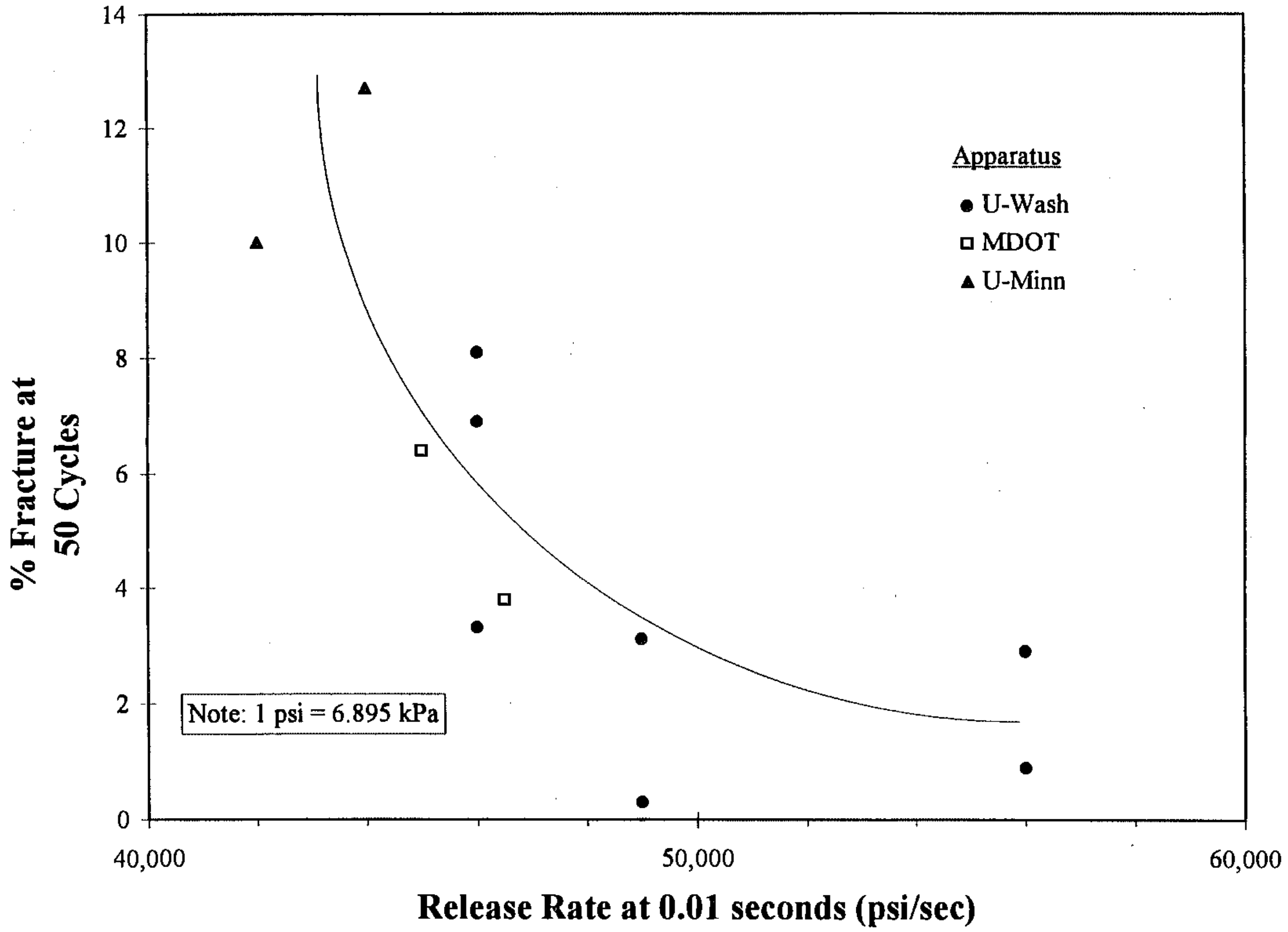

Figure #14. % Fracturing vs Release Rate for Evergreen

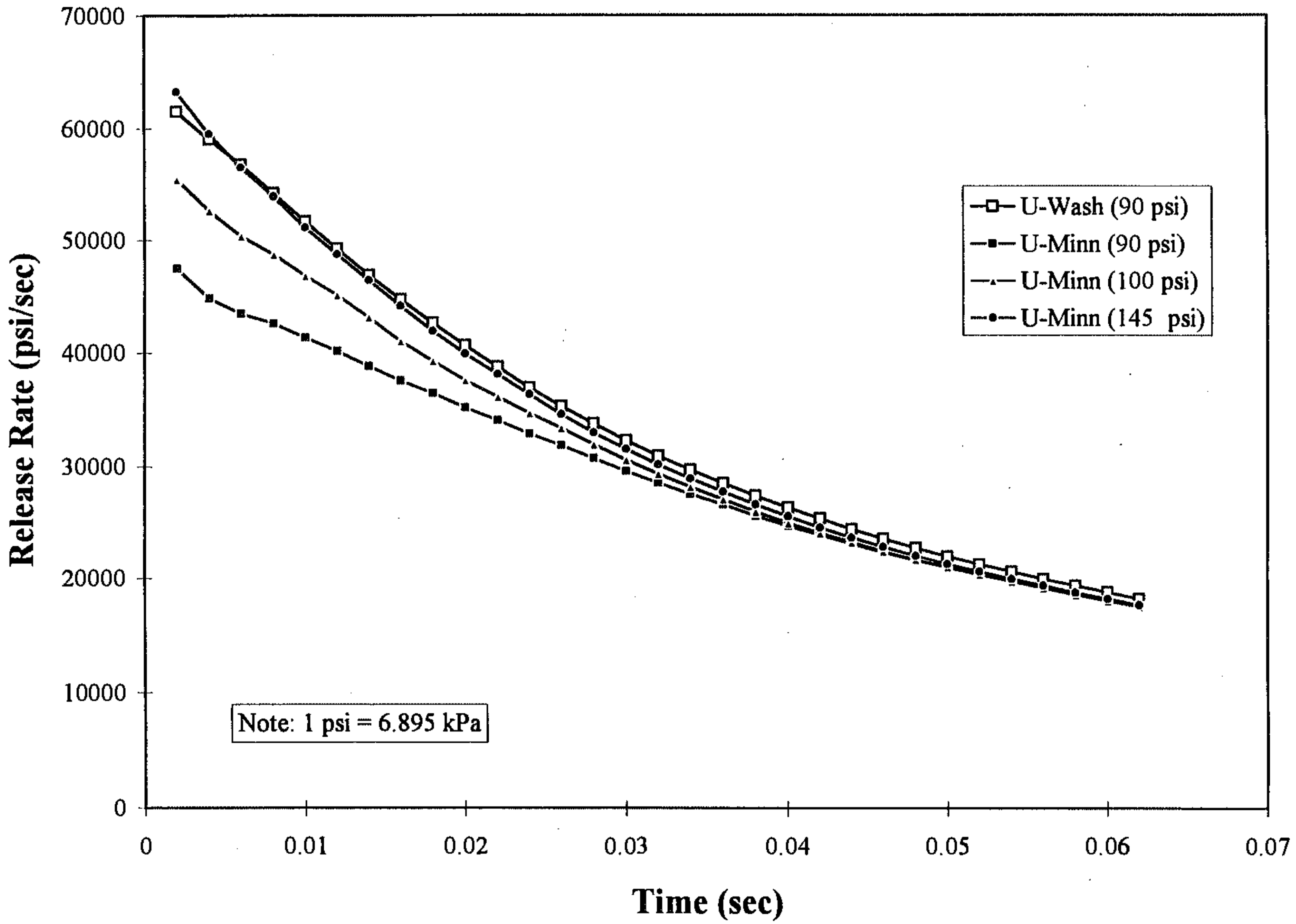

Figure #15. Calibration of U Minn WHFT Apparatus to U Wash

Table 23. % Fracture with Release Rate Variation
for Evergreen 19-25-mm

Test Number	Solenoid Pressure/Apparatus		
	90 psi / U-Minn	150 psi / U-Minn	90 psi / U-Wash
	% Fracture @ 50 Cycles	% Fracture @ 50 Cycles	% Fracture @ 50 Cycles
1	10.0	6.4	6.9
2	12.7	3.6	8.1
3	N/A	N/A	3.3

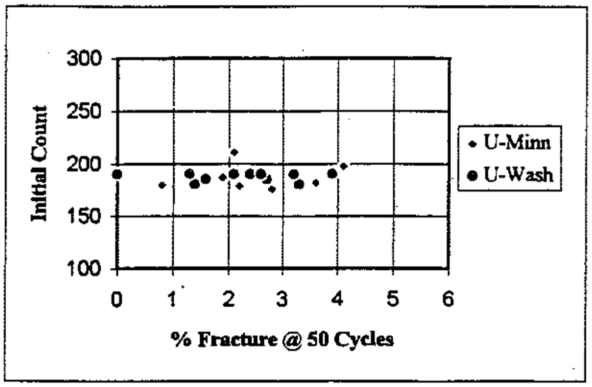

Figure #16. Initial Count vs % Fracture for Bundy Hill (30-35) 19 - 25-mm

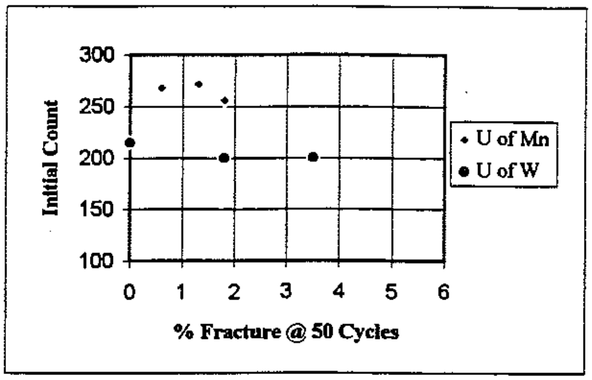

Figure #17. Initial Count vs % Fracture for Bruce Mines (95-10) 19 - 25-mm

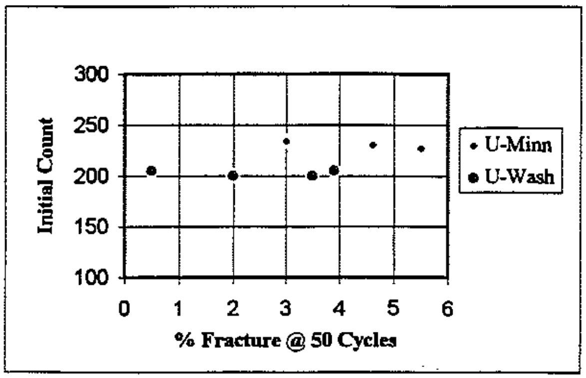

Figure #18. Initial Count vs % Fracture for Celotex (07-20) 19 - 25-mm

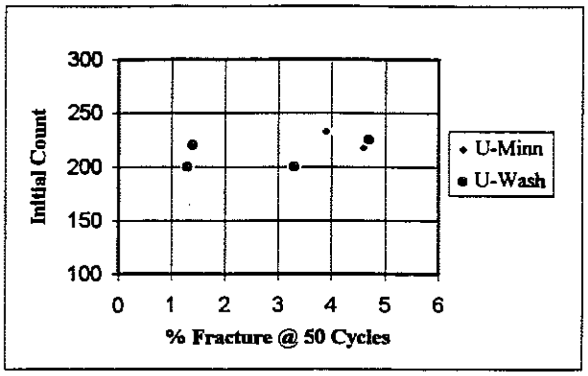

Figure #19. Initial Count vs % Fracture for City Limits (17-20) 19 - 25-mm

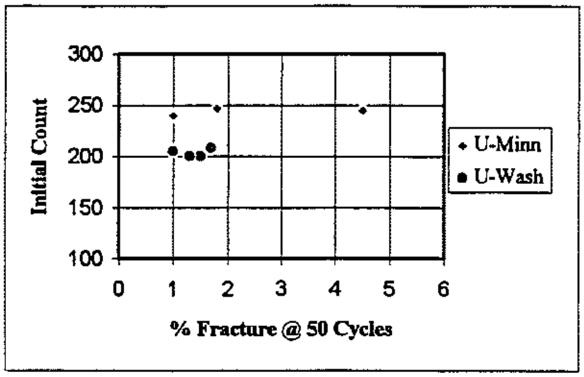

Figure #20. Initial Count vs % Fracture for Dennison Farms (58-09) 19 - 25-mm

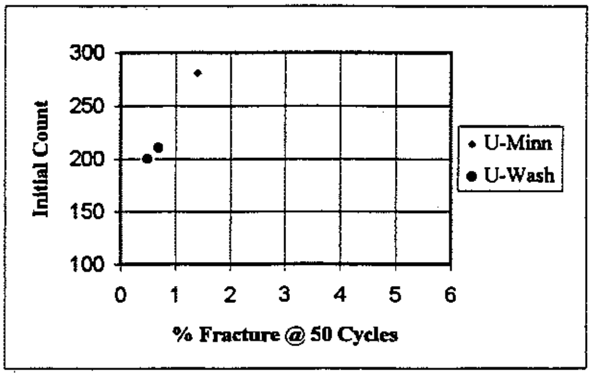

Figure #21. Initial Count vs % Fracture for Drummond (17-66) 19 - 25-mm

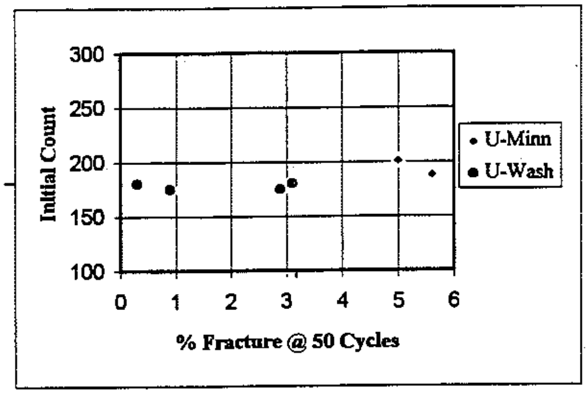

Figure #22. Initial Count vs % Fracture for Evergreen (52-78)19 - 25-mm

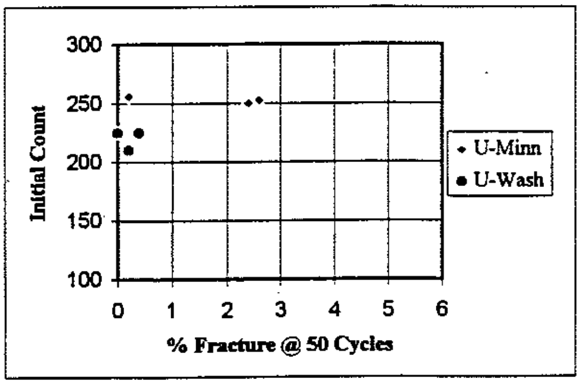

Figure #23. Initial Count vs % Fracture for France Stone (93-03) 19 - 25-mm

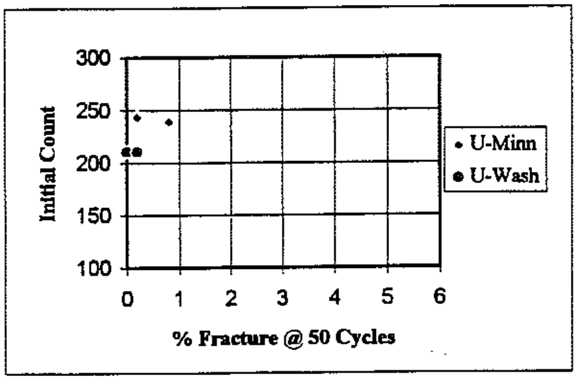

Figure #24. Initial Count vs % Fracture for Marblehead (93-01) 19 - 25-mm

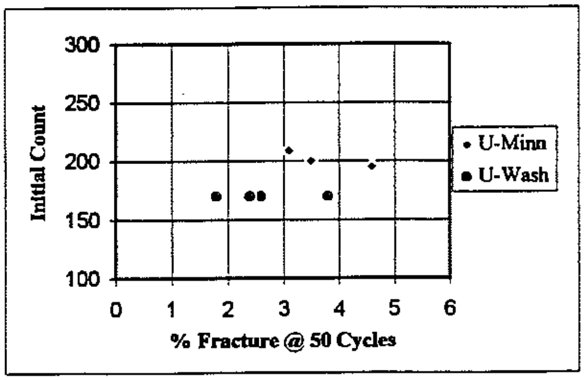

Figure #25. Initial Count vs % Fracture for Michigan Foundation (82-06) 19 - 25-m

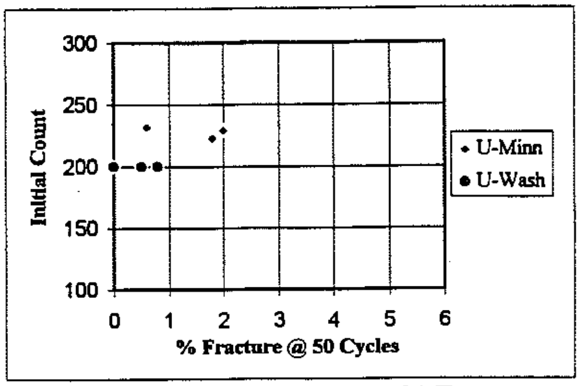

Figure #26. Initial Count vs % Fracture for Maybee (58-04) 19 - 25-mm

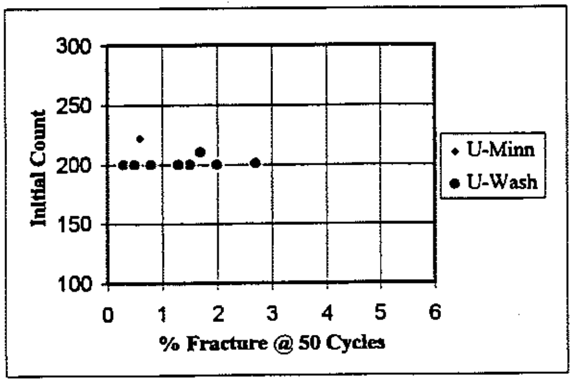

Figure #27. Initial Count vs % Fracture for Rockwood (58-08) 19 - 25-mm counts increase while Bruce Mines (95-10) and City Limits (17-20) (which contain few or no openly-porous particles) do not. A trend is not clear for Bundy Hill (30-35) because all tests used about the same number of particles. Within the carbonate group, it appears that most differences in fracture are between labs and are not due to particle counts.

It was hypothesized that that there is a difference in some aspect of the hydrodynamic forces that cause particle fracture when the relative volumes of aggregate and water are varied in the test chamber. It is also possible that the few observed trends are due between-lab variations (due to variations in pressure release rates, for example, as noted previously), since the particle counts and fracture percentages in these cases were both higher at Minnesota than at Washington.

Some additional testing was performed at the University of Minnesota to further investigate the effects of particle count on hydraulic fracture test results. These tests were performed on sample of the Evergreen aggregate source (52-78) using the Minnesota and MDOT hydraulic fracture test apparati, and the results are presented in Table 24 and Figure 28. These data still do not indicate any clear trends in the effect of particle count on hydraulic fracture test results.

All of the testing described in this subsection was performed before the Minnesota-funded study identified the more effective equipment calibration criterion. Further testing should be performed along the same lines described above, except using test apparati that have been calibrated to produce comparable results. However, it seems unlikely that particle count significantly affects test results as long as the test chamber is not overfilled, which can result in particle fractures as the lid compresses the aggregate. It is more likely that observed variations in particle fracture rates with varying particle counts are attributable to equipment release rates and random variations in the sample composition and properties.

5.2.6 Hydraulic Fracture Tests of Recycled Concrete Aggregate

Three sources of recycled Michigan concrete aggregate were tested in the hydraulic fracture apparatus: a recycled gravel concrete, a recycled limestone concrete and a recycled slag concrete. The recycled gravel concrete was obtained from a portion of I-94 near Brighton, MI; the recycled limestone concrete and recycled slag concrete were obtained from unknown pavement sources through a Michigan aggregate supplier.

Only particles in the 19- to 25-mm (3/4- to 1-in) particle size range were tested in the hydraulic fracture apparatus. All three aggregates were used to make concrete freeze-thaw beams, which were prepared and tested at the U-Minn in accordance with AASHTO T 161 Procedures B and C. The recycled gravel concrete was also freeze-thaw tested at the University of Michigan in accordance with MTM 115, resulting in a dilation of 0.048% per 100 cycles. The results of the hydraulic fracture tests and AASHTO T 161 freeze-thaw tests are presented in Table 25 and Figure 29.

These data do not suggest any clear trends between incidence of particle fracture and freeze-thaw test dilation for any of the recycled concrete aggregate sources. All three sources exhibited levels of fracturing that would be considered indicative of potential freeze-thaw

Table #24. Data for Evaluation of Effects of Sample Count on Test Results (Evergreen 19-25-mm)

Appartus	Initial Particle Count	%Fracture @ 50 cycles	% Mass Loss @ 50 Cycles
U-Minn	180	10.0	0.90
U-Minn	204	12.7	0.70
MDOT	180	6.4	0.70
MDOT	210	3.8	0.30

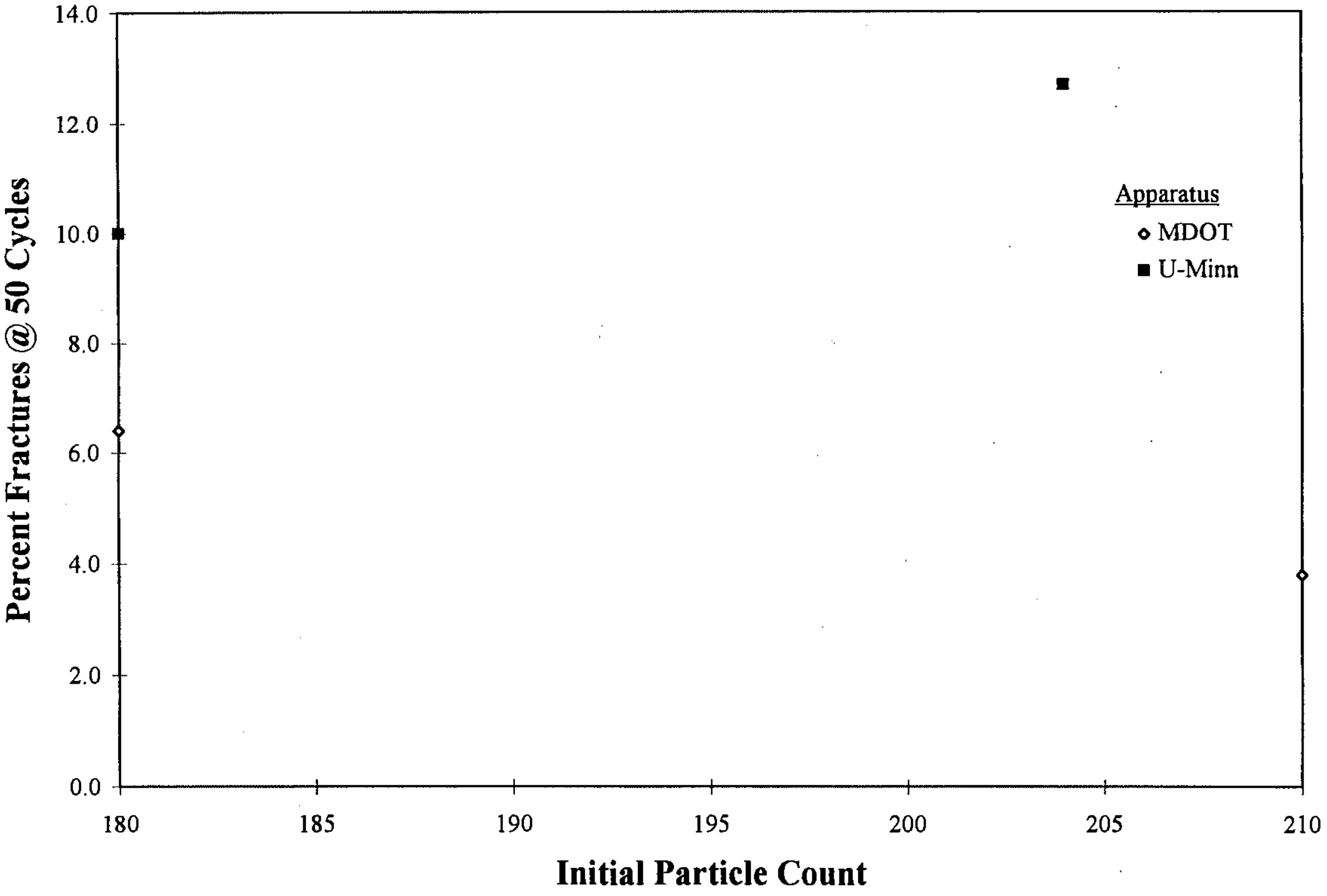

Figure #28. Particle Count vs Fracture for Evergreen 19-25-mm

Table #25. Dilation and Fracture Data, 19-25 mm Recycled Aggregate
(U-Minn Freeze-Thaw and WHFT Data)

Source	% Dilation / 100 Cycles		% Fracture @ 50 Cycles for 3 tests	
	Procedure C	Procedure B	Mean Value	Standard Deviation
Recycled Limestone	0.0657	0.0490	7.6	2.0
Recycled Slag	0.0029	0.0013	9.5	0.2
Recycled Gravel	0.0137	0.0116	5.8	2.8

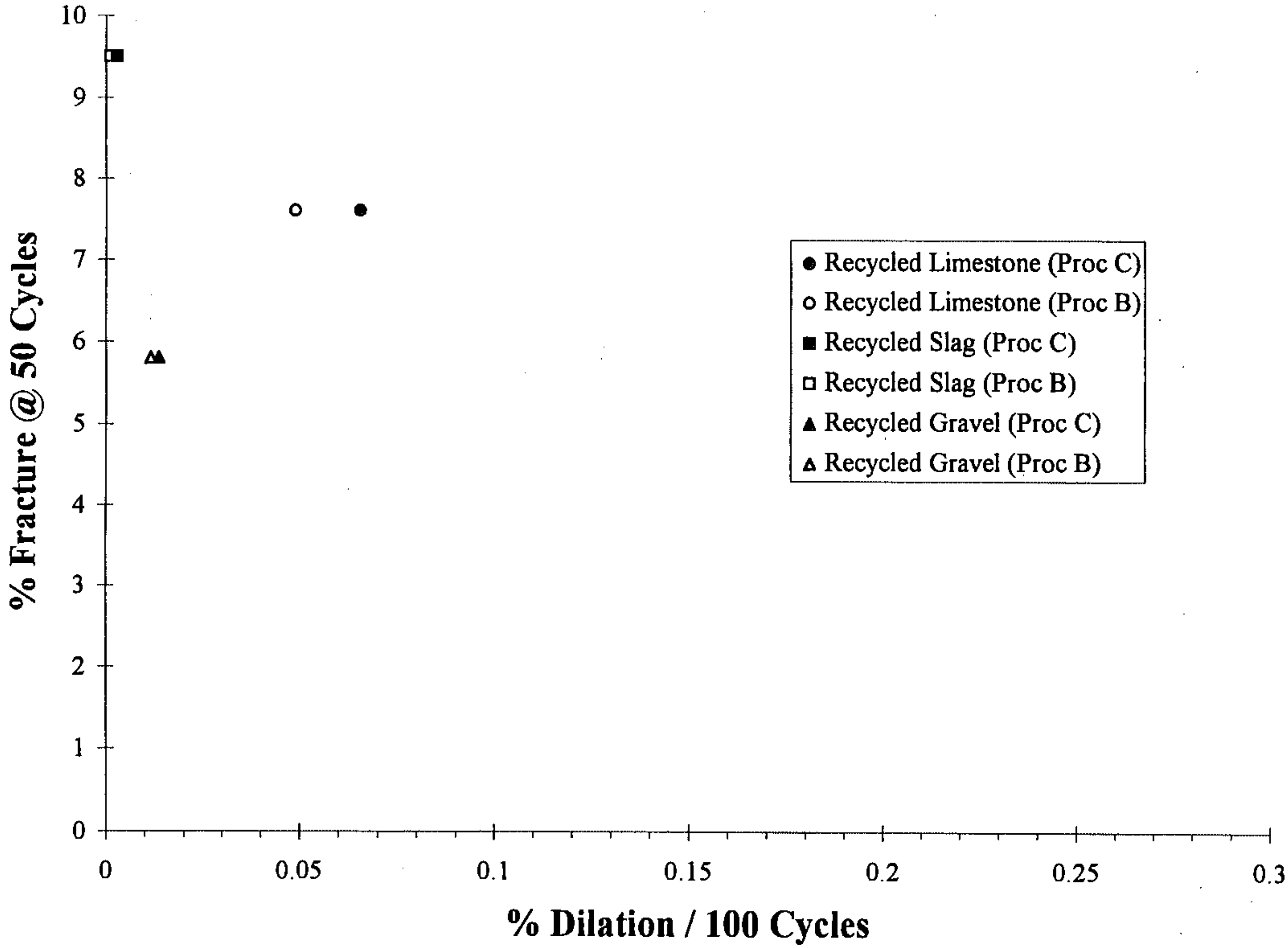

Figure #29. % Fracture vs Dilation, 19-25-mm Recycled Aggregates
(AASHTO T 161 Procedures, U-Minn Data)

problems in natural aggregates, but dilation data obtained using AASHTO T 161 (MTM 115 vacuum-saturation equipment is not available at U-Minn) indicate a broad range of freeze-thaw durability that does not correlate with the fracture data. It is possible that the hydraulic fracture test results for recycled concrete materials are influenced by the many factors, including the natural aggregate pore structure and particle strength, the bond strength between the old mortar and the natural aggregate, the presence of any weakened planes or fractures produced during the crushing process, and other considerations. It is also possible that the current test protocol should be modified for this type of aggregate to produce a better correlation with dilation (e.g., use a different chamber pressure, different release rate, different acceptance/rejection criteria, etc.).

The preceding comments and conclusions are made on the basis of only a few tests of a few recycled concrete aggregate sources. A much broader test program should be undertaken to more fully evaluate the potential of the hydraulic fracture test for quickly assessing the freeze-thaw durability potential of recycled concrete aggregate sources; for MDOT, this program should include companion tests of freeze-thaw beams prepared and tested in accordance with MTM 115. Until further testing and evaluations are done, the hydraulic fracture test does not appear to be suitable for use in assessing the freeze-thaw durability of recycled concrete aggregates.

5.3 Special Studies

A number of special studies were conducted as a part of this research project. The specific special studies are described in the following sections.

5.3.1 WHFT Calibration

As a part of the testing conducted to determine the critical test parameters that must be specified in order to assure that duplicate WHFT equipment produce the same results, as series of tests were conducted with varying chamber pressures and release rates. These tests used the Rockwood aggregate in the 19-25 mm. size range. The results are summarized in Figure 30, which shows the HFI values for various release rates and chamber pressures. The numerical values plotted in the figure are the HFI values.

The figure shows that the lowest release rate produced less fracturing (higher HFI values) than higher rates. The figure also shows that for a given release rate, the fracturing decreases for both high and low chamber pressures. There appears to be a central area defined by a minimum, release rate and a specific chamber pressure that appears to optimize fracturing. A minimum release rate of 210,000 kPa/sec. over a duration of 0.01 seconds and a chamber pressure of 7,930 kPa is suggested for WHFT testing.

5.3.2 Deleterious Materials

The ability of the WHFT procedure to identify materials classified as deleterious by MDOT was investigated by preparing specimens with exactly 25 percent (by number of particles) of a specific deleterious material combined with a durable dolomite. The deleterious materials used were typical sandstone, siltstone, shale, clay-ironstone, and chert particles. All pieces were in the 19-25 mm size range.

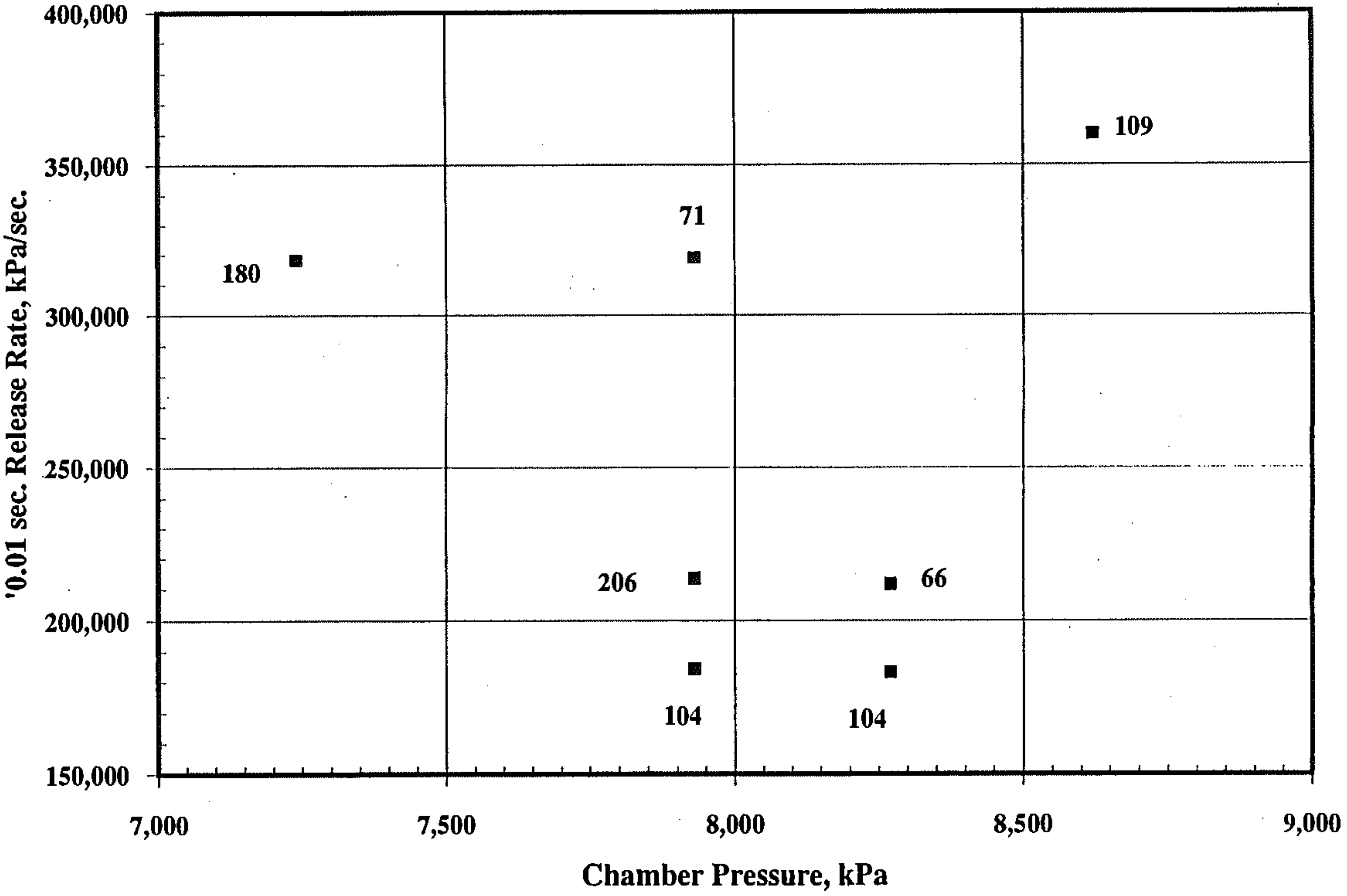

Figure # 30 Effect of Release Rate and Chamber Pressure on HFI.

Table 26. Deleterious Materials Results.

Specimen	Hydraulic Fracture Index
Dolomite plus 24% Sandstone	75
Dolomite plus 25% Siltstone	6
Dolomite plus 25% Shale	13
Dolomite plus 25% Clay Ironstone	9
Dolomite plus 25% Chert	>500

5.3.3 Silane Treatment

In order to avoid problems with high absorption rates, the aggregate is treated with a silane-based sealer. This method is explained in Appendix A, pp. A-16 to A-19.

The question of whether or not the silane treatment was necessary was addressed by testing specimens of both the deleterious materials and the Bundy Hill aggregate with and without silane treatment. These results are presented in Table 27.

As can be seen the use of silane generally had no effect on the results of the hydraulic fracture tests. However, the silane did reduce the fracture rate of sandstone particles, which fractured much less when the silane treatment was used. The silane treatment appears to not have a detrimental effect on the results. In a few limited cases, the sandstone and the specific Illinois limestone mentioned in Appendix A, the silane treatment allows aggregates that would be expected to fracture to actually fracture.

Table 27. Effect of Silane Treatment.

Specimen	Untreated HFI	Treated HFI
Dolomite plus 24% Sandstone	225	75
Dolomite plus 25% Siltstone	10	6
Dolomite plus 25% Shale	9	13
Dolomite plus 25% Clay Ironstone	12	9
Dolomite plus 25% Chert	>500	>500
Bundy Hill (Gravel)	106	99

6. CONCLUSIONS AND RECOMMENDATIONS

The hydraulic fracture test, in its current form, is not yet ready for adoption by the Michigan Department of Transportation or other agencies as a technique for consistently and reliably predicting the results of freeze-thaw durability testing according to MTM 115. It is still believed, however, that the hydraulic fracture test will eventually be successfully developed into a rapid test for accurately assessing the freeze-thaw durability of many types of concrete aggregate.

The testing documented in this report has significantly advanced the development of this test and laid the groundwork for final developmental work. Several modifications of the test equipment and procedures were developed and tested under this contract. These modifications resulted in substantial improvements in test repeatability and reduction of variability due to previously unknown sources. These modifications include:

- The incorporation of an electro-pneumatically-acutated pressure release valve, eliminating the manually-operated valve that was part of the equipment developed under the SHRP study and reducing the variability of the rate at which the valve is opened during pressure release.
- The addition of neoprene lining to the pressure chamber lids to reduce the incidence of particle fracture due to contact with the lids during testing.
- Revisions to the computation of the hydraulic fracture index, basing the index on the number of cycles to produce 5 percent particle fracturing rather than 10 percent. This was effectively an increase in the scale of the index to account for the reduction in particle fractures that were produced after the pressure chamber lids were lined with neoprene.

The following section highlights some of the additional conclusions drawn from the project work and the recommendations provided in section 6.2 provide some direction for future research and development activities. A specific work plan for future research is not provided because such a plan should be developed by the persons proposing that research in the context of the results of this study and other ongoing studies.

6.1 Conclusions

1. Early attempts to develop a large chamber for hydraulic fracture testing that would produce the same results being obtained with the smaller apparatus that evolved from the original SHRP study were unsuccessful.

2. The Hydraulic Fracture Index (HFI), as it is currently defined, did not correlate well with dilations measured according to MTM 115. Computed fracture rates and mass losses produced by the hydraulic fracture test correlated much better with MTM 115 dilations.

3. Correlations between computed fracture rates, mass loss and MTM 115 dilations were improved when the size of the sample considered was increased (i.e., the results of three small chamber runs were combined to produce a single test result). This finding reinforces the need to develop a larger test chamber.

4. The hydraulic fracture test produced large amounts of fracturing of "soft" particles, such as sandstone, that are considered deleterious but are not necessarily associated with large dilations or poor freeze-thaw durability. The frost resistance of aggregate sources that contain even small quantities of sandstone may not be adequately assessed using current hydraulic fracture test parameters (i.e., HFI, computed particle count and mass loss). Even greater amounts of fracturing were produced in materials containing similar quantities of siltstone, shale and clay ironstone.

5. The hydraulic fracture test generally failed to produce fractures in chert particles, which are strongly associated with poor freeze-thaw durability (especially popouts). The frost resistance of aggregate sources that contain significant quantities of chert may not be properly assessed using current hydraulic fracture equipment and procedures.

6. Some "quick-screen" tests, such as absorption capacity, specific gravity and carbonate content (for gravel sources only) were found to be correlated with MTM 115 dilation.

7. The use of the hydraulic fracture equipment and procedures developed under this study minimizes the potential for variability in test results due to different operators.

8. Identically designed hydraulic fracture equipment can produce significantly different test results for identical aggregate samples if the apparati are not properly calibrated. An equipment "calibration" or adjustment technique developed after this study was complete appears to reduce the variability in test results between different apparati to undetectable levels.

9. Hydraulic fracture test results do not seem to be affected by the number of particles included in the test chamber as long as the chamber is not overfilled, which can result in particle crushing as the lid compresses the aggregate.

10. The hydraulic fracture test, in its current form, does not appear to be suitable for use in assessing the freeze-thaw durability of recycled concrete aggregates.

11. The use of silane (to control the rate of absorption and produce fracture rates that are indicative of probable freeze-thaw performance) generally had no effect on the results of hydraulic fracture tests performed on selected aggregates in this study. However, the silane did reduce the fracture rate of sandstone particles and was useful in producing more realistic test results for at least one other aggregate source in a previous study. On this basis, the continued use of silane for pretreating the aggregates is recommended.

12. MDOT petrographic examinations of Marblehead (93-01) freeze-thaw beams suggested that the mechanism of failure in these beams was rooted in the transition zone between aggregate and paste, not within the aggregate itself. Test of unconfined aggregate (i.e., unconfined freeze-thaw or hydraulic fracture test) would not be expected to correlate well with this mechanism for aggregates such as Marblehead.

6.2 Recommendations

1. The Michigan DOT should not yet adopt the hydraulic fracture test as either a replacement or a screening test for MTM 115, which assesses the potential freeze-thaw durability of coarse aggregates intended for use in portland cement concrete.

2. The Michigan DOT should make use of the results of this study and the results of other studies of the hydraulic fracture test to complete the development of the hydraulic fracture test. Specific factors that deserve additional consideration are described below.

3. A second attempt should be made to develop a large chamber hydraulic fracture test apparatus because the results of both this study and the original SHRP study documented the reduction in test variability and improvement in accuracy that results from the testing of larger samples. Results of tests currently underway at the University of Minnesota and partially documented in this report indicate that it may now be possible to "calibrate" a larger chamber so that it will produce results comparable to those obtained using the smaller chamber used in this study.

4. Efforts should be devoted to improving the way in which the rate of aggregate fracture is determined in the current test procedure, which does not adequately differentiate between various possible modes of fracture (e.g., one piece breaking into two similarly-sized pieces, one piece breaking into three or more similarly-sized pieces, one piece breaking into many small pieces, etc.). This is due to the use of only the 9.5- and 4.75-mm (3/8-in and #4) sieves to separate the aggregate pieces and estimate the number of fractured particles after testing. These misleading estimates of fracturing lead to poor correlations with the results of other tests (e.g., MTM 115). Research currently underway at the University of Minnesota is attempting to address this issue by using a more extensive series of sieves to separate the aggregate pieces after testing. It is believed that this type of procedural modification might provide more accurate estimates of particle fracture rates and might correlate better with MTM dilations and other freeze-thaw test results.

5. After the chamber size and particle fracture estimation issues described above have been addressed, research efforts should focus on validation of the test equipment and procedures. This work should include:

- Retesting of all of the aggregate sources considered in this project using the new procedures and larger chamber equipment (since the dilation and fracturing characteristics of these sources is now extremely well documented) to generally validate the revised equipment and procedures;
- Tests (both hydraulic fracture and MTM 115) of additional gravel samples that do not contain significant quantities of sandstone and/or chert in order to provide better documentation of the ability of the hydraulic fracture test to predict the dilative characteristics of concrete produced using these materials;
- Tests (both hydraulic fracture and MTM 115) of additional samples of aggregates containing varying quantities of known deleterious and "soft" particles to better determine the content thresholds above which unacceptable dilation may develop and to determine whether different acceptance criteria should be developed for such materials;
- Additional freeze-thaw testing of the samples that were "spiked" with chert to determine whether the "unbreakable" chert submitted for hydraulic fracture testing is actually expansive in freeze-thaw;
- Petrographic examinations should be performed on slices of Bundy Hill (30-35) and City Limits (17-20) freeze-thaw beams (taken through chert and sandstone, respectively) to determine the mode and location of fracture initiation; and
- Tests (both hydraulic fracture and MTM 115) of additional samples of recycled concrete aggregates and slag aggregates to determine whether current procedures can be used to predict the dilation characteristics and freeze-thaw durability of these materials and, if so, to determine appropriate criteria for acceptance and rejection.

6. Consideration should be given to making an aggregate "pick" the first step in any evaluation of frost resistance. In this step the aggregate composition and origin is determined. This would provide a basis for selection of subsequent durability tests. For example, gravels containing significant quantities of chert would be directed to MTM 115 or some other durability screening test, but not to the hydraulic fracture test, which currently fails to fracture chert.

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Appendix A

Background, Principles, and Theories of the Washington Hydraulic Fracture Test

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THE WASHINGTON HYDRAULIC FRACTURE TEST: DEVELOPMENT AND MECHANISM

1.0 INTRODUCTION

One of the specific tasks of research funded by the Strategic Highway Research Program (SHRP) contract on the resistance of concrete to freezing and thawing was the development of a rapid method for identifying aggregates susceptible to damage from freezing and thawing (often termed D-cracking). This report summarizes the SHRP research efforts in developing the test (called the Washington Hydraulic Fracture Test) and includes a description of the mechanism believed to be responsible for the function of the test.

2.0 BACKGROUND

2.1 D-Cracking Occurrence

D-cracking is the term used to describe the distress in concrete that results from the disintegration of coarse aggregates after they have become saturated and have been subjected to repeated cycles of freezing and thawing. [1] D-cracking is observed most often in pavements, though it can occur in structural concrete as well. The occurrence of D-cracking in concrete containing aggregates known to be susceptible is most often associated wwith the portions of the concrete exposed to moisture intrusion from multiple directions. Examples of such exposure include pavement joints (where water can intrude from both the top and bottom of the concrete slab, as well as the vertical joint face), especially the intersections of longitudinal and transverse joints (which provide mutually perpendicular sources of intrusion) and the bases of concrete walls and/or columns where snow is allowed to accumulate (preventing the draining of water during periodic thaws).

Although D-cracking has been known to exist since the 1930s [2], a fast, reliable, reproducible, easily performed, and inexpensive test for identifying aggregates susceptible to D-cracking has not been developed to date.

2.2 Conditions Necessary for D-cracking

The mechanisms of D-cracking have not yet been completely clarified and continue to be intensively studied. [3] Original research was based primarily on the fact that water expands 9 percent when it freezes. Thus, the term "critical saturation" was coined to describe the point at which the aggregate pores were 91.7 percent saturated and, therefore, assumed to be susceptible to damage due to freezing and thawing. Further research has found that deterioration due to freezing and thawing can affect aggregates with lower degrees of saturation. [4]

To date, four theories have gained wide acceptance in describing the mechanisms of frost action. [5] Although most of these theories were originally used to describe the frost action in cement paste, they are also applicable to aggregates. [6] The first was the hydraulic pressure theory Powers proposed in 1945. This was followed by the diffusion and growth of capillary ice theory constructed by Powers and Helmuth in 1953, the dual mechanism theory by Larson and Cady in 1969, and the desorption theory by Litvan in 1972.

Powers' hydraulic pressure theory proposes that destructive stresses can develop if water is displaced to accommodate the advancing ice front in concrete. [7] If the pores are critically saturated, water will begin to flow to make room for the increased ice volume. Hydraulic pressures generated during the water flow will be dependent upon the length of the flow path, the rate of freezing, the permeability of the concrete, and the viscosity of the water. The concrete and aggregate will crack if the hydraulic pressure exceeds its tensile strength.

Further studies by Powers and Helmuth revealed that the hydraulic pressure theory did not account for continued dilation of some specimens and shrinkage of other specimens at constant temperature. [8] They therefore proposed that the formation of ice produces a relatively concentrated alkali solution at the freezing site. Unfrozen water will, in turn, move toward the site because of the differences in solute concentrations in a process similar to osmosis. Hence, the pressure developed was called osmotic pressure.

Research by Larson and Cady showed the migration of water out of specimens during freezing, which they felt supported the hydraulic pressure theory. [9] However, they also noted continued dilation of concrete specimens after the equipment indicated that freezing had ceased. They attributed these dilations to the hydraulic pressures generated by the increase in the specific volume of water during the "ordering" or change of state from bulk water on the ice and pore surfaces to adsorbed water.

Litvan's desorption theory proposes that cooling in a partially-saturated porous system produces excess vapor pressure in the pores due to the reduced solubility of water in air at lower temperatures. These vapor pressure differentials between the inside and outside of the porous material force water to migrate out. [10] As in Powers' theory, the aggregate will rupture if the hydraulic pressures generated during migration exceed the tensile strength of the aggregate.

Given the above theories of frost damage, actual D-cracking can occur only when 1) the concrete contains D-cracking susceptible aggregates in a sufficient number and of a large enough size, 2) the concrete is exposed to sufficient moisture, and 3) the concrete is exposed to repeated cycles of freezing and thawing. The significance of these conditions is:

1) Sufficient Number and Size of D-cracking Aggregate - The concrete must contain D-cracking susceptible aggregate. This emphasizes the importance of identifying D-cracking susceptible aggregate. There must be a sufficient number of D-cracking susceptible pieces to cause damage to the concrete as a whole rather than simply localized damage such as a popout. This means that blending a sufficient quantity of non-susceptible

aggregate with a D-cracking susceptible aggregate can result in acceptable performance. The size of the D-cracking susceptible aggregate pieces must be large enough to cause D-cracking. Reducing the maximum aggregate size has been found to decrease the D-cracking potential of the aggregate in concrete. [11] This means some other measure of the aggregate (such as pore length) in addition to the pore size distribution is important in determining D-cracking susceptibility.

2) Sufficient Moisture Exposure - The concrete must be exposed to a sufficient amount of moisture in order for D-cracking to occur. Pavement concrete made with D-cracking susceptible aggregates may show substantial deterioration near joints or cracks that allow water intrusion, while having no deterioration apparent in cores taken as little as one meter (three feet) away from the crack or joint. [12, 13] Details allowing for additional water intrusion, such as the intersection of transverse and longitudinal joints, could result in increased deterioration.

3) Sufficient Freezing - The concrete must freeze a sufficient number of times for the D-cracking to be noticeable. Often, five to ten or more years are required for D-cracking to become apparent. [11] Depth of freezing also has an effect on D-cracking, with mild climates producing D-cracking that resembles shallow spalls near joints rather than the traditional deterioration starting at the bottom of concrete slabs.

None of the conditions necessary for D-cracking are related to the air-void system in the concrete. Though deterioration of the paste portion of the concrete due to inadequate entrained air could accelerate D-cracking progression by allowing more moisture to enter the concrete, a properly air-entrained concrete can still develop D-cracking when the above three conditions are met.

This necessity for multiple conditions in order for D-cracking to occur means that field records of aggregate performance can possess a degree of unreliability. Specifically, a history of acceptable performance of an aggregate could simply reflect the fact that the concrete containing the aggregate in question may not have been exposed to sufficient moisture and/or cycles of freezing and thawing. A test to identify D-cracking susceptible aggregates should be able to identify whether the aggregate has potential for D-cracking if concrete made with the aggregate receives the necessary temperature and moisture exposure.

3.0 CURRENT IDENTIFICATION PROCEDURES

The complete interrelationship of variables affecting the performance of aggregates in concrete has resulted in a diversity of tests that try to provide a reliable means of separating durable and non durable aggregates. [14] The test methods developed to date to identify the resistance of aggregate to frost action can be placed into two primary groups. [8, 9] One group consists of tests that try to simulate the environmental conditions to which the concrete aggregate is exposed. The other group comprises tests that correlate aggregate properties (termed index properties) with known field performances and/or results from environmental tests.

3.1 Environmental Simulation Tests

The environmental simulation tests include the following:

a. Sulfate Soundness
b. Unconfined Aggregate Freezing and Thawing
c. Rapid Freezing and Thawing
d. Powers Slow Cool
e. VPI Single-Cycle Slow-Freeze

3.1.1 Sulfate Soundness (AASHTO T104)

This test is favored by many over other test methods because of the small amount of equipment involved and the short amount of time required to run the test. [14] In the

Sulfate Soundness test, aggregate is soaked in a sodium or magnesium sulfate solution and then dried. Repeated cycles result in salt crystal growth in the aggregate pores. The expansive forces generated by the crystal growth supposedly simulate the expansive forces caused by the formation of ice in aggregate pores. However, the major natural cause of disintegration in aggregates, according to some theories, is the hydraulic pressure produced when water attempts to leave the zone of freezing. [14] The growth of the sulfate crystals occurs as the aggregate is dried in an oven; hence, the crystal formation is not generating hydraulic pressures. Additionally, the sulfate test does not account for the effects of confining the aggregate by mortar, which determines the rate and amount of moisture movement into and out of the aggregate.

3.1.2 Unconfined Aggregate Freezing and Thawing (AASHTO T103)

The Unconfined Aggregate Freezing and Thawing test is an outgrowth of the sulfate test. [14] The test has three variations; however, the basic procedure consists of subjecting the aggregate to repeated freezing in water and thawing in air. As with the sulfate test, the unconfined freezing and thawing test does not duplicate confinement of the aggregate by mortar. This test can be less reproducible because of the number of variables involved. These variables include rate of cooling and final temperature, rate of thawing, the moisture conditions of the samples before each cycle, and the length of time the samples remain frozen and thawed.

3.1.3 Rapid Freezing and Thawing (AASHTO T161)

The Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing has two methods, A and B. Method A consists of freezing and thawing specimens in water, and Method B consists of freezing specimens in air and thawing them in water. [15] The test can be conducted with concrete cylinder or prism specimens, although prism specimens are most commonly used. [1] A cycle of freezing and thawing is completed by lowering the specimen temperature from 4°C (40°F) to -18°C (0°F) and raising it back to 4°C (40°F) within a 2- to 5-hour period. Specimen length change and a durability factor, calculated from relative dynamic modulus of elasticity (ASTM C215), are determined from the test. Measurements are initially taken and repeated after no more than every 36 cycles until completion. The test is completed when the modulus is reduced to 60 percent of the initial modulus, or after a specified number of cycles (typically 300 or 350).

Presently, standard specifications provide limited guidance on what constitutes good or poor performance. Except for ranking in relative order of frost resistance, no criteria have been established for the acceptance or rejection of aggregates on the basis of AASHTO T161 [16], although some states have established their own criteria. Furthermore, although this test better simulates the confining nature of mortar in concrete, aggregate evaluations may take nearly five months to complete. [17]

3.1.4 Powers Slow Cool (ASTM C671)

In this test, concrete specimens are placed in a constant temperature bath and maintained at 1.7°C (35°F). [18] Once every two weeks, the specimens are immersed in a water-saturated kerosene bath and the temperature is lowered from 1.7°C (35°F) to -9.4°C (15°F) at the rate of 2.8C° (5F°) per hour. Length changes are measured during cooling. After having cooled, the specimens are returned to the original water bath. The test is terminated once the specimens exceed critical dilation or until the specimens have completed a desired number of cycles. Critical dilation is the dilation during the last cycle before the dilation begins to increase by a factor of two or more. The number of cycles during which the difference between successive dilations remains constant is termed the period of frost immunity. Some highly frost resistant aggregates may never produce critical dilations.

As with the Rapid Freezing and Thawing test, this test is time intensive and requires costly equipment.

3.1.5 VPI Single-Cycle Slow Freeze [19]

This test uses concrete specimens made and cured in accordance with ASTM C192. Stainless steel strain plugs are placed, 25 cm (10 in.) apart, into the prisms. Initial measurements of transverse frequency, weight, and length are recorded. Specimens are placed in a freezing apparatus with an air temperature of -18°C (0°F). Length change measurements are made at 5- to 15-minute intervals over a 4-hour cooling period.

From the results, two correlations are made. The first is temperature versus length change. The minimum 2.8°C (5°F) temperature slope is the minimum slope that can be found, within a 2.8°C (5°F) or more range, on the length change-temperature curve obtained during the first freeze of a specimen. The second correlation is time versus length change. The cumulative length change is plotted versus time, and the time slope is determined as the minimum slope that can be found within a 1/3-hour or greater time range.

This test requires approximately three days to perform once curing is completed. It has been found to produce fairly accurate results for distinguishing between very durable and non durable aggregates. However, for aggregates of questionable durability, it is recommended that the Rapid Freezing and Thawing test should be performed.

3.2 Aggregate Index Property Tests

The tests developed to correlate aggregate properties to field performance are generally relatively quick compared to the environmental simulation tests described above, and with one exception require relatively inexpensive equipment. These tests include the following:

a. Mercury Intrusion Porosimeter

b. Iowa Pore Index

c. Absorption-Adsorption

d. Petrographic Analysis

3.2.1 Mercury Intrusion Porosimeter

One of the major ways of determining the pore size distribution of a porous solid is by mercury porosimetry, [20] which is based on a relation presented by Washburn. The mercury intrusion porosimeter apparatus has been used in many studies of the pore characteristics of aggregates. [17, 21, 22, 23, 24, 25] The non-wetting liquid is almost always mercury because of its low vapor pressure and relative inertness to chemical reaction with the aggregate, and because it is non-wetting for most surfaces. [21] However, the problems with this test include the following:

1. Washburn's equation is for pores that are cylindrical and interconnected. This is not normally the case with aggregate. The pore size distribution is weighted toward smaller pore sizes because the void volumes of pores with entrances narrower than the body, termed "ink-bottle pores," will be recorded according to the entrance size.
2. Values must be assumed for the contact angle and surface tension of the non-wetting liquid.
3. The sample size is very small, usually 2-5 grams. Therefore, the test may not yield a representative result, especially when testing heterogeneous sources.
4. The equipment is expensive and requires special handling.

3.2.2 Iowa Pore Index Test

The Iowa Pore Index Test (IPIT) was developed on the basis of earlier evidence that D-cracking is related to freezing and thawing and, more specifically, to the pore sizes of coarse aggregate. [17] The objective in developing the test was to readily identify a correlation between an aggregate's susceptibility to critical saturation and its potential to cause D-cracking. [1]

The test procedure consists of placing a 9000-gram oven-dried aggregate sample in a modified air pressure meter container, filling the container with water, and then applying 241 kPa (35 psi) of air pressure. [17] The test procedure defines the "primary load" as the amount of water injected during the first minute. This reading is assumed to correspond to the filling of the aggregate's macropores. A large primary load is considered to be an indication of a beneficial limestone property.

The amount of water injected between 1 and 15 minutes is defined as the "secondary load" and is believed to represent the quantity of water injected into the aggregate's micropore system. The secondary load is used as the "Pore Index" test result.

Aggregates with histories of producing D-cracking concrete have had Pore Index readings of 27 ml or more. [1, 17] Comparing the IPIT and the mercury intrusion porosimeter to aggregate field performance, Shakoor and Scholer concluded that the pore index test is a reliable, less expensive, and quicker replacement for mercury intrusion porosimetry. [24] They also state that the IPIT results are more representative of the parent rock because of the large sample volume used.

Other studies have found problems with the IPIT. [26, 27] These problems include variable and erroneous results for aggregates with reasonably rapid rates of early absorption and no discernible trends in the results from gravels. Furthermore, IPIT cannot indicate to what extent a reduction in maximum aggregate size will improve performance, and the test does not discriminate between absorption by a few highly porous particles or absorption by many moderately porous particles.

3.2.3 Absorption-Adsorption

An extensive study of D-cracking by Klieger et al., in Ohio, included an attempt to develop a test that would distinguish between durable and non-durable aggregate and that would require a minimum amount of sample preparation, time, and test equipment. [28] They developed an absorption-adsorption test and compared the test results to pavement service records.

After conducting this test with a large variety of aggregate sources, they concluded that the absorption-adsorption test tended to be overly conservative in its identification of durable and potentially non-durable aggregates. The test predicted poor resistance to freezing and thawing for a large percentage of material from several sources with good service records.

3.2.4 Petrographic Analysis (ASTM C295)

Many studies of aggregate resistance to freezing and thawing have incorporated petrographic analyses either to identify aggregate properties that affect concrete durability or to predict aggregate performance in freezing and thawing tests. [9, 19, 29, 30, 31, 32] Petrographic examination is a visual examination and analysis of aggregate in terms of both lithology and individual particle properties. [33, 34] It requires the skills of a well trained and experienced petrographer. The examination uses small sample sizes, which require a large amount of work to provide accurate results. [34] Also, the analysis is not able to provide definite specification limits because information so obtained is the result of subjective appraisal by the petrographer and can be reduced to a numerical quantity only through personal interpretation. [33]

4.0 WASHINGTON HYDRAULIC FRACTURE TEST (SHRP VERSION)

4.1 Goals and Objectives

The importance of identifying D-cracking susceptible aggregates has led to a considerable number of aggregate identification test procedures. Unfortunately, the more reliable of the procedures may require eight weeks or longer, expensive equipment, and/or highly skilled operators. In response to this problem, the goal of the SHRP research was the development of a rapid, reliable test method for identifying D-cracking susceptible aggregates. The ideal procedure should also be relatively inexpensive so as not to be prohibitive for routine testing. The following sections will describe the procedure, called the Washington Hydraulic Fracture Test, that has been developed.

4.2 Test Description

The test essentially consists of:

1. placing a washed, oven-dried, and surface treated (to be hydrophobic) specimen of known mass, number of particles, and size range (smallest size is retained on 12.5 mm sieve) into the pressure chamber,
2. bolting the chamber shut and filling it with water,
3. applying an internal pressure of 7930 kPa (1150 psi) to the chamber, and
4. rapidly releasing the chamber pressure.

After ten repetitions of steps 3 and 4 the specimen is removed from the chamber, oven dried, and the particles counted. Two days are required for specimen preparation including washing, oven drying, surface treating, and grading, and an additional day for each ten pressurization cycles (actual operator time is less than one hour per specimen per day). After the last pressurization day the results are analyzed. This gives a total of eight days required for test results. Results are given in terms of the increase in number of pieces larger than the 4.75 mm (#4) sieve as a percentage of the total number of initial pieces for each ten cycles of pressurization. This is termed the "percent fracture". From these values an index is determined that indicates the number of pressurization cycles necessary to produce 10 percent fracturing. Lower values of this index indicate a more D-cracking susceptible aggregate than aggregates with higher values.

4.3 Test Mechanism

This test method is based on the assumption that the internal pressures expected in concrete aggregates during freezing and thawing can be simulated by subjecting sample aggregates, submerged in water, to high pressures. As the external chamber pressure increases, the water penetrates into smaller and smaller pores. If this external pressure is rapidly released, air compressed within any pores will push the water back out, thereby simulating the internal pressures generated during freezing. Fracturing of the aggregate should result if the pressure in the pores cannot be dissipated quickly and the aggregate is unable to elastically accommodate the high internal pressure.

Kaneuji et al. observed qualitative correlations between concrete durability and pore size distributions of aggregates. [23] At a constant total pore volume, aggregates with smaller pore sizes result in a lower durability. For aggregates with similar predominating pore sizes, a greater pore volume results in a less durable aggregate. By correlating aggregate service records with mercury porosimeter studies, Marks and Dubberke found that, with one exception, the non durable aggregates analyzed exhibited a predominance of pore sizes in the 0.04- to 0.2-μm diameter range, while aggregates with good to excellent service records had a majority of pores that were larger than the 0.04- to 0.2-μm diameter pore sizes. [17]

Using Washburn's equation:

$$P = 4T \cos \theta / d \tag{1}$$

where:
T = surface tension (72 dynes/cm for water)
θ = contact angle (assumed 0° for water)
d = pore diameter

absolute pressures of between 1450 kPa (210 psi) and 7240 kPa (1050 psi) can be used to penetrate water into pore diameters within the range of 0.2 to 0.04 μm.

The advantages of this proposed test are as follows:

a. theoretically, the test should be able to simulate the hydraulic pressures that many believe cause D-cracking in nondurable aggregates;

b. the cost for special equipment is relatively low;

c. compared to existing tests, this test should be relatively fast, and therefore, economical; and

d. the uniform pressure applied to individual aggregate particles within the chamber, along with the rate of pressure application, final pressure, and holding time, which can be easily standardized and controlled, make this test easily reproducible.

The testing procedure depends upon pressure being required to force water into the aggregate pores, followed by the release of the pressure causing a critical gradient of pressure from inside to outside the aggregate of sufficient magnitude to cause fracturing. Winslow [27] pointed out that some aggregates absorb water extremely quickly. If an aggregate is at a relatively high degree of saturation prior to pressurization in the Washington Hydraulic Fracture procedure, the pressure gradient necessary for fracture after the pressure was released may not develop. This was found to be true for a limestone used early in the test development. Winslow absorption rates [27] are shown in Figure A-1 for four aggregates. Both gravels and one of the limestones (the non-D-cracking limestone) have similar absorption rates while the other limestone (which is D-cracking susceptible) has a much higher absorption rate. While the absorption rate itself is not an indicator of D-cracking susceptibility [27], this higher absorption rate could prevent the above fracture mechanism from working with rapidly absorbing aggregates.

A way to avoid problems with aggregates having high absorption rates is to make the pores hydrophobic rather than hydrophilic. One method of accomplishing this is to treat the aggregate with a silane-based sealer. The literature [35] suggests that the primary effect of the silane is to change the water/solid contact angle in the aggregate pores. This would not affect the pore size, but would effect the absorption of water into the pore by surface tension effects. Figure A-2 is a plot of the absorption rates for the untreated and treated ILA limestone. As can be seen, the absorption rate is indeed decreased. The slower absorbing limestone (ILB) was also treated for comparison purposes. Previous work [36, 37] has shown that the treatment does not affect the fracture results of slow-absorbing aggregates.

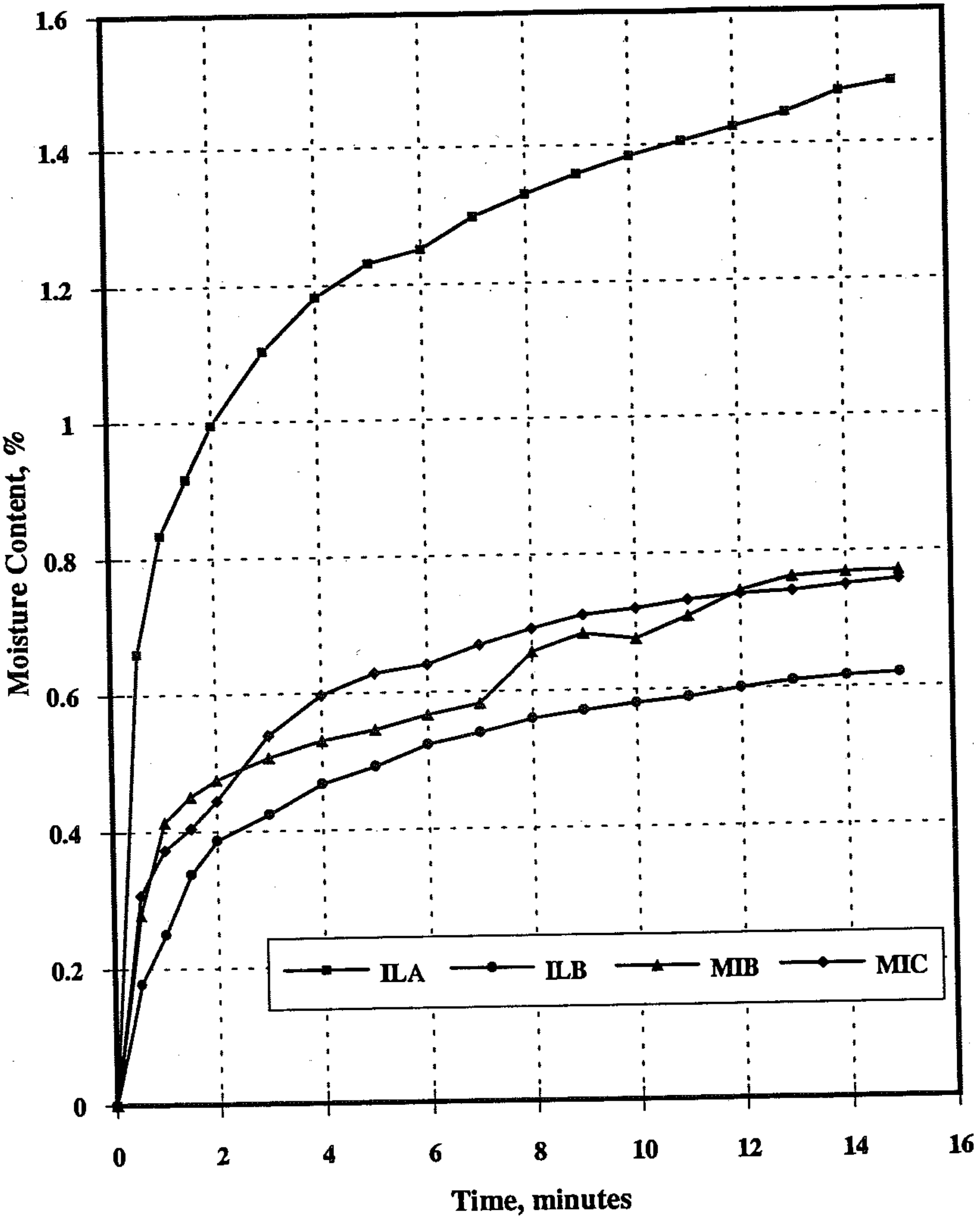

Figure A-1. Winslow [27] Absorption Rates for Four Aggregates. [38]

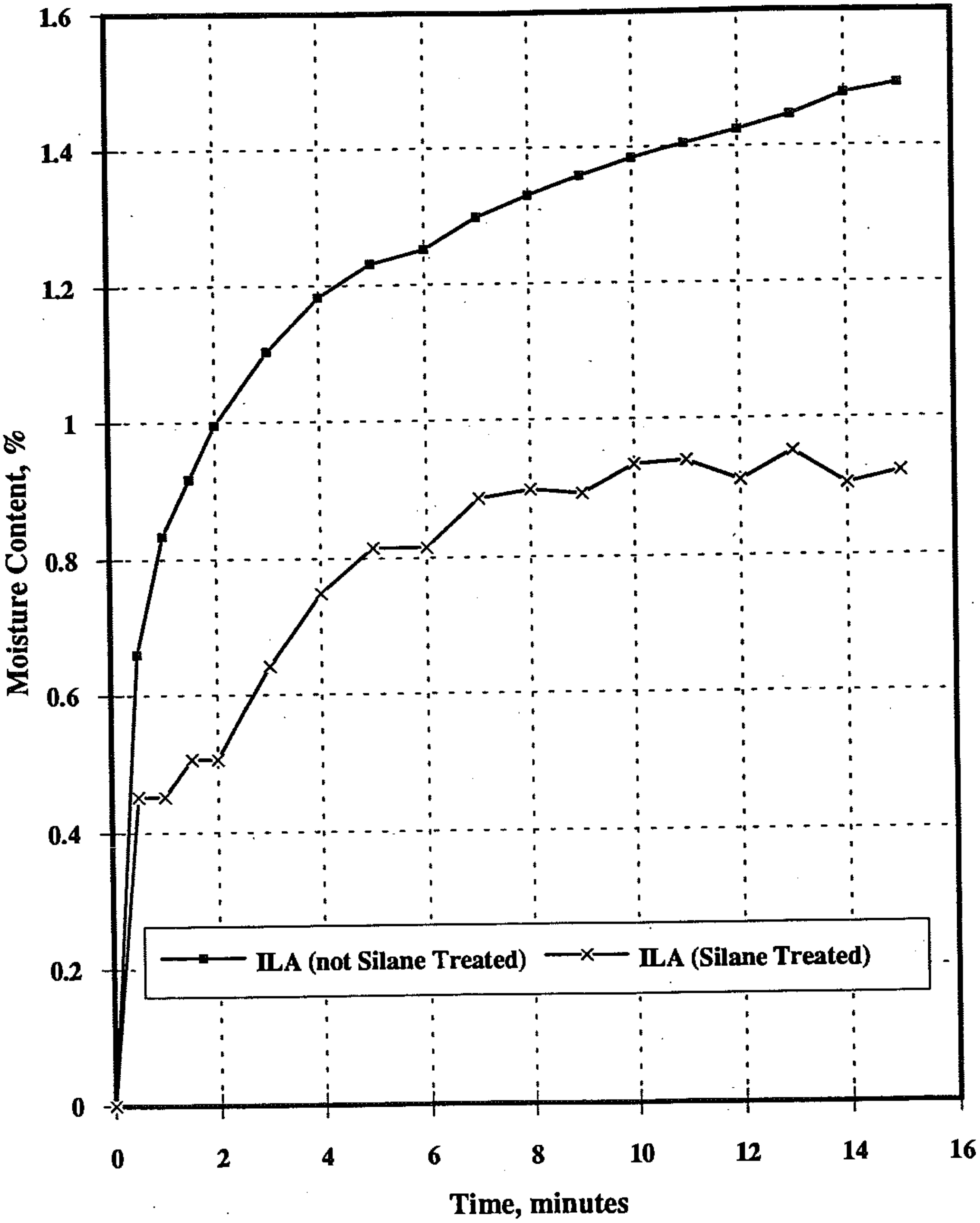

Figure A-2. Effect of Silane Treatment on Winslow [27] Absorption Rates for D-Cracking Susceptible Limestone. [38]

4.4 Equipment

The main part of the testing apparatus is the pressure chamber, which is developed from a commercially available 100 bar (10,000 kPa, 1500 psi) pressure membrane extractor (similar to the equipment described in ASTM D 3152). A second top plate replaces the normal bottom plate and drain line provided with the extractor. The three holes already threaded into the pressure chamber cylinder are used for pressure application/relief, water supply, and water drainage. The water drain hole has a piece of copper tubing inserted to act as a siphon so that the chamber may be drained while in a horizontal position.

The pressure application/relief mounting consists of two valves. One valve isolates the pressure chamber from the pressure source, compressed nitrogen. The other valve serves as an overflow valve during filling and a pressure relief valve at the end of testing.

A rock tumbler is used after removing the aggregate sample from the test apparatus to insure that the effect of sample handling is relatively uniform, therefore making any mass loss associated with handling also uniform. In addition, the tumbler is used to facilitate fracturing initiated by the pressurization process.

4.5 Test Procedure

Before testing, each aggregate sample was separated by sieving into appropriate size ranges: 12.5 mm (1/2 in.) to 19.0 mm (3/4 in.) and 19.0 mm (3/4 in.) to 31.5 mm (1-1/4 in.). The size ranges used were relatively narrow in order to determine particle size effects of D-cracking potential. The aggregate was then washed and oven dried at 120°C (250°F) to constant mass (normally at least 12 hours). Each specimen was then immersed for thirty seconds in a water-soluble solution of silane sealer, drained, and again oven dried at 120°C (250°F) for at least 12 hours.

The pressure chamber held a sample size of approximately 3200g (7.0 lbs) depending upon the range analyzed. This is equivalent to approximately 450 pieces in the 12.5 mm (1/2 in.) to 19 mm (3/4 in.) range and 150-225 pieces in the 19.0 mm (3/4 in.) to 31.5 mm (1-1/4 in.) range. Each sample was initially placed in the rock tumbler for one minute and then all pieces passing the 9.5 mm (3/8 in.) were removed. This was to insure that no pre-existing fractures are in the aggregates prior to testing. The sample initial weight and number of particles were then determined and recorded. Next, the sample was placed in the chamber and the chamber bolted shut. The chamber was then turned on edge, so that the pressure application/relief mount was vertical, and was filled with water up to the overflow/relief valve. Once the water supply and overflow/relief valves were secured, the selected pressure was applied by opening the valve separating the chamber and the compressed nitrogen. The pressure was maintained for five minutes. The top valve was then closed to isolate the chamber from the compressed nitrogen and the overflow/relief valve was rapidly opened, thereby quickly releasing the pressure within the chamber. The small amount of water that sprayed out when the relief valve was opened was replaced by briefly refilling the chamber with water. After thirty seconds the chamber was re-pressurized. The pressure was then released after two minutes. An additional eight cycles of two minutes of pressure followed by pressure release and no pressure for thirty seconds were applied. At the end of the ten total cycles, the pressure chamber was drained and opened. The specimen was oven dried at 120°C (250°F) overnight. The following day, the sample was tumbled for one minute in a rock tumbler and then separated using 9.5 mm (3/8 in.) and No. 4 sieves. All particles of the sample retained on both sieves were weighed and counted. The material retained on the 9.5 mm (3/8 in.) sieve was subjected to an additional ten pressurization cycles. The pressurization was repeated for a total of 50 cycles (five days) for each aggregate sample.

4.6 Analysis of Results

The example results discussed below are for only one D-cracking susceptible and one non-D-cracking susceptible gravel. Results for additional materials are presented under "Reliability and Repeatability".

4.6.1 Calculations

A primary value determined from testing is the percentage of fractures. Percentage of fractures is calculated by dividing the number of additional pieces by the original number of aggregate pieces prior to any pressurization. Materials retained on the 9.5 mm (3/8 in.) sieve are counted as whole pieces (that is, they count as "one"), while particles passing the 9.5 mm (3/8 in.) sieve but retained on the 4.75 mm (No. 4) sieve are counted as partial pieces (the number of pieces is divided by two in the calculation). This is shown in Equation 2, below:

$$FP_i = 100\,(n4_i/2 + n_i - n_0)/n_0 \qquad (2)$$

where FP_i is the percent fractures after "i" pressurization cycles,

$n4_i$ is the number of pieces passing the 9.5 mm (3/8 in.) sieve but retained on the 4.74 mm (No. 4) sieve after "i" pressurization cycles,

n_i is the number of pieces retained on the 9.5 mm (3/8 in.) sieve after "i" pressurization cycles, and

n_0 is the initial number of pieces tested.

The percentage of fractures is used to calculate an index value called the hydraulic fracture index (HFI), which can be thought of as number of cycles necessary to produce 10 percent fracturing. It is determined by one of the following methods, depending upon what the percentage of fracturing is after 50 cycles of pressurization.

If 10 percent fracturing is achieved in 50 or fewer cycles, the HFI is calculated as a linear interpolation of the number of cycles that produced 10 percent fractures:

$$HFI = A + 10 * [(10 - FP_A)/(FP_B - FP_A)] \tag{3a}$$

where A is the number of cycles just prior to achieving 10 percent fracturing,

FP_A is the percentage of fracturing just prior to achieving 10 percent fracturing, and

FP_B is the percentage of fracturing just after achieving 10 percent fracturing.

If 10 percent fracturing is not achieved in 50 pressurization cycles, the HFI is calculated as an extrapolation from no fracturing at 0 cycles through the amount of fracturing at 50 cycles:

$$HFI = 50 * (10/FP_{50}) \tag{3b}$$

where FP_{50} is the percentage of fracturing after 50 pressurization cycles.

The mass of material as a percentage of the original specimen that is no longer retained on the 9.5 mm (3/8 in.) sieve is called the percentage of mass loss (ML), and is determined as follows:

$$ML_i = (100/m_0) * [m_0 - (m4_i + m_i)] \tag{4}$$

where ML_i is the percentage of mass loss after "i" cycles of pressurization,

$m4_i$ is the cumulative mass of the material passing the 9.5 mm (3/8 in.) sieve but retained on the 4.75 mm (#4) sieve after "i" pressurization cycles,

m_i is the mass of the pieces retained on the 9.5 mm (3/8 in.) sieve after "i" pressurization cycles, and

m_0 is the initial mass of the specimen tested.

While no interpretation has yet been determined for the ML values, this value is calculated and recorded for possible future use.

4.6.2 Pressure Effect

According to the test mechanism proposed above, the magnitude of the pressure difference between the inside and the outside of an aggregate piece should affect the amount of fracturing produced. Original development of the procedure started with a pressure of 7240 kPa (1050 psi). When this pressure did not produce much fracturing, the pressure used was increased 690 kPa (100 psi) from 7240 kPa (1050 psi) to 7930 kPa (1150 psi). Figures A-3 and A-4 display changes in the percentage of fracturing due to this increase in pressure. As would be expected, an increase in pressure (and very likely the pressure difference across the aggregate particle when the pressure is released) results in an increase in the percentage of fractures occurring. This suggests that higher pressure differences will produce better results since more fracturing occurs. However, it should be noted that above some pressure, many non-susceptible aggregates would be expected to show considerable fracturing. This would make differentiating between durable and non-durable materials difficult. Some trials at 10,000 kPa (1500 psi) did indeed cause considerable fracturing in a non-D-cracking aggregate.

4.6.3 Aggregate Size Effect

Next, a comparison is made with regard to change in particle size. Figures A-5 and A-6 present comparisons of +19.0 mm (3/4 in.) and -19.0 mm (3/4 in.) of the susceptible and non-susceptible gravels, respectively. It is shown that there is a decrease in the percentage of fractures as the size of the material tested is reduced. This would be expected since the flow path in the -19.0 mm (3/4 in.) material should be much shorter than the +19.0 mm (3/4 in.) material, therefore providing a shorter path for release of hydraulic pressures developed. This size effect agrees with Stark and Klieger [2], Traylor [26] and others who reported that D-cracking severity was reduced by reducing the maximum aggregate size.

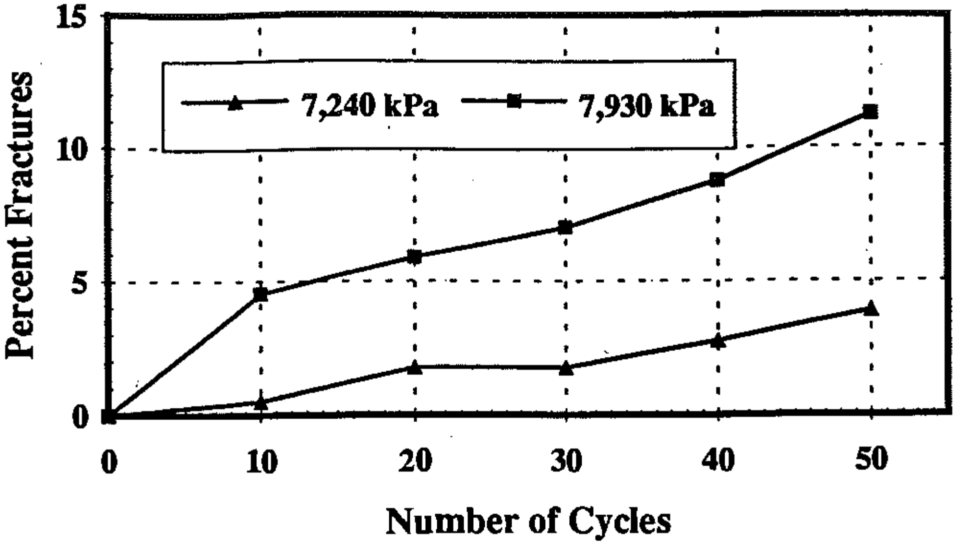

Figure A-3. Effect of Chamber Pressure on Fracturing, Non-Durable Gravel. after Janssen and Snyder [38]

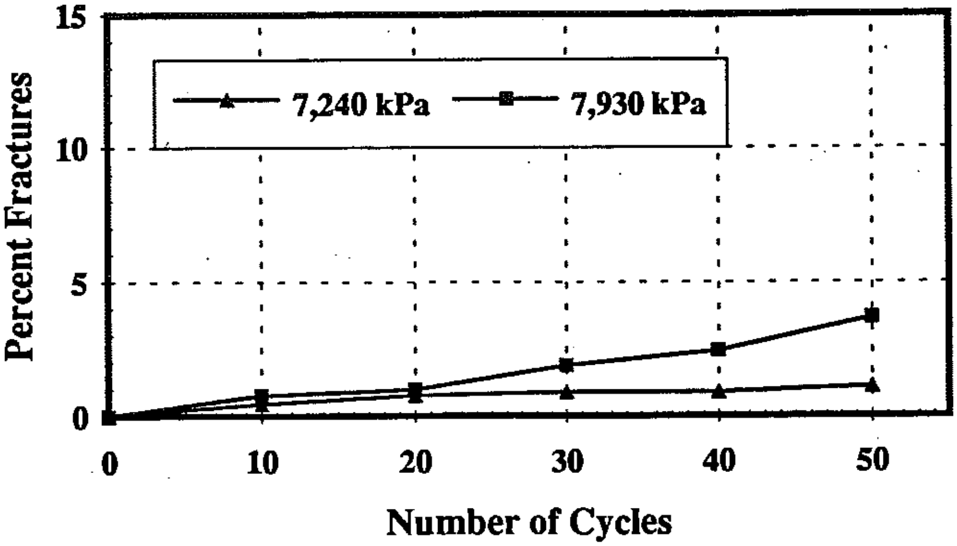

Figure A-4. Effect of Chamber Pressure on Fracturing, Durable Gravel. after Janssen and Snyder [38]

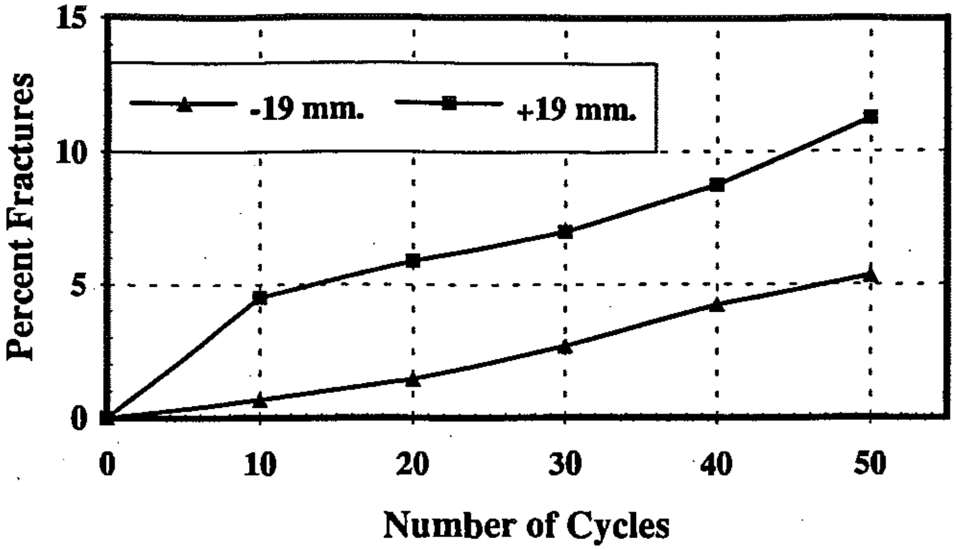

Figure A-5. Effect of Aggregate Size on Fracturing, Non-Durable Gravel. after Janssen and Snyder [38]

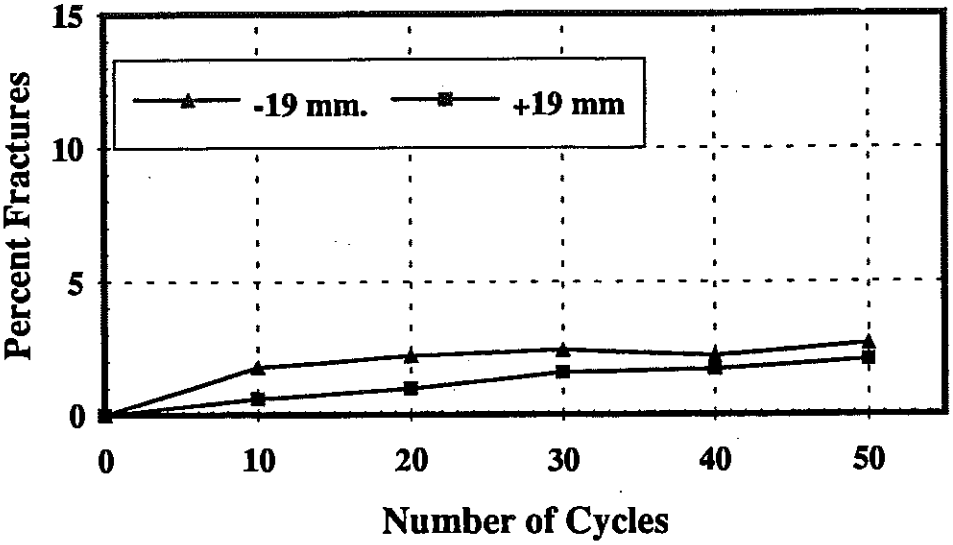

Figure A-6. Effect of Aggregate Size on Fracturing, Durable Gravel. after Janssen and Snyder [38]

4.7 Reliability and Repeatability

Table A-1 shows the HFI values for 13 aggregate sources for materials in the 19.0 mm (3/4 in.) to 31.5 mm (1-1/4 in.) size range. Seven of these aggregates were reported as D-cracking susceptible by the agencies that provided them while six of the aggregates were reported as non-D-cracking susceptible. All of the D-cracking susceptible aggregates, with the exception of one of the limestones from Iowa, had HFI values below 60. The D-cracking susceptible Iowa limestone with the high HFI value has had durability factors as determined in accordance with AASHTO T161 of 65, 83, and 87 in a properly air-entrained mix [39].

All of the aggregates except one that were reported as durable had HFI values above 100. The one durable aggregate that gave a low HFI value was described by the Iowa department of Transportation as a coarse-grained crinoidal limestone with a low specific gravity (2.57) and a high absorption (2.5%). [39] No explanation has been developed to explain the high degree of fracturing of this aggregate in the Washington Hydraulic Fracture Test.

Table A-1. WHFT Results, +19 mm (3/4 in.) Size. [38]

SAMPLE ID	SOURCE STATE	FIELD PERFORMANCE	HYDRAULIC FRACTURE INDEX
IAB	IOWA	D-CRACKING	49
IAD	IOWA	D-CRACKING	* 160
IAF	IOWA	D-CRACKING	43
ILA	ILLINOIS	D-CRACKING	52
MIA	MICHIGAN	D-CRACKING	43
OHC	OHIO	D-CRACKING	11
OHD	OHIO	D-CRACKING	32
IAA	IOWA	NON D-CRACKING	106
IAC	IOWA	NON D-CRACKING	45
IAE	IOWA	NON D-CRACKING	109
ILB	ILLINOIS	NON D-CRACKING	286
MIB	MICHIGAN	NON D-CRACKING	241
WAA	WASHINGTON	NON D-CRACKING	129

* Aggregate has produced durability factor (DF) values of 65, 83, and 87 in AASHTO T161 when tested by Iowa Department of Transportation. This aggregate is reported as being D-cracking susceptible in the field. [39]

Table A-2 shows the coefficients of variation for the HFI values as determined from a range of sample sizes. This table suggests that the minimum sample size should be in the range of 600-800 pieces in order to provide a reliable HFI value. Unfortunately this was not known when many of the samples were being solicited for the SHRP test development, and adequate sample sizes were not available for many of the aggregates tested. Qualitative observation of the testing suggests that this sample size limitation is more critical for bedrock sources than for gravel sources. With gravels, the fractures appear to frequently occur in the same rock type for a given source. This suggests that for gravels, the majority of the particles are either clearly durable or clearly non-durable. The durability of a source would then depend upon the number of non-durable particles included in the material. It would appear that individual particles from bedrock sources, however, are less variable in pore structure within a given range of a given ledge. It would also appear that bedrock sources of marginal durability could be more likely to contain particles that were less clearly durable or non-durable (that is, the individual particles have borderline durabilities). Therefore, a larger specimen size would be necessary to provide reliable results.

Table A-2. Effect of Sample Size on Variability. [38]

SAMPLE ID	Coefficient of Variation, Percent (Average Number of Particles)			
IAA	114 (185)	35 (370)	25 (555)	9 (740)
IAB	41 (177)	15 (354)	-	-
IAC	27 (145)	10 (290)	-	-
IAD	72 (181)	29 (362)	12 (543)	-
IAE	52 (156)	23 (312)	-	-
IAF	37 (183)	20 (366)	-	-

Between laboratory variabilities are shown in Table A-3. The agreement between tests run at UW and tests run at MSU are in most cases quite good, despite the lower than ideal sample sizes (shown as "Average Number of Particles" in the table). The testing at UI provided consistently higher HFI values. Recalibration of the pressure gauge on the equipment used at UI determined that it was off by about 350 kPa (50 psi). The effect of pressure magnitude on HFI values has been previously discussed. Great care must to be taken in the future to make sure that the pressure gauges are not vibrated out of calibration during shipping.

Table A-3. Between-Laboratory Results. [38]

SAMPLE ID	UW HFI (# part)	MSU HFI (# part)	UI HFI (# part)
IAA	106 (924)	91 (200)	148 (178)
IAB	50 (530)	54 (190)	162 (178)
IAC	45 (435)	38 (180)	91 (110)
IAD	168 (725)	40 (200)	230 (138)
IAE	109 (468)	95 (190)	165 (314)
IAF	44 (550)	26 (180)	51 (195)

4.8 Chamber Modification

The sample size effects discussed above suggest that a larger chamber capable of testing a larger sample size would be appropriate. Previous discussions have also suggested that the pressure magnitude and the rate of pressure release could play critical roles in producing the desired fracturing in non-durable aggregates. Figure A-7 shows the average pressure release history for the original chamber pressurized to 7,930 kPa (1150 psi). A linear fit to the central portion of the curve gave a pressure release rate of 209,000 kPa/sec. (30,300 psi/sec) over a range of over 3,610 kPa (520 psi). Ideally, an alternate chamber (either larger or of a different design) should produce a similar

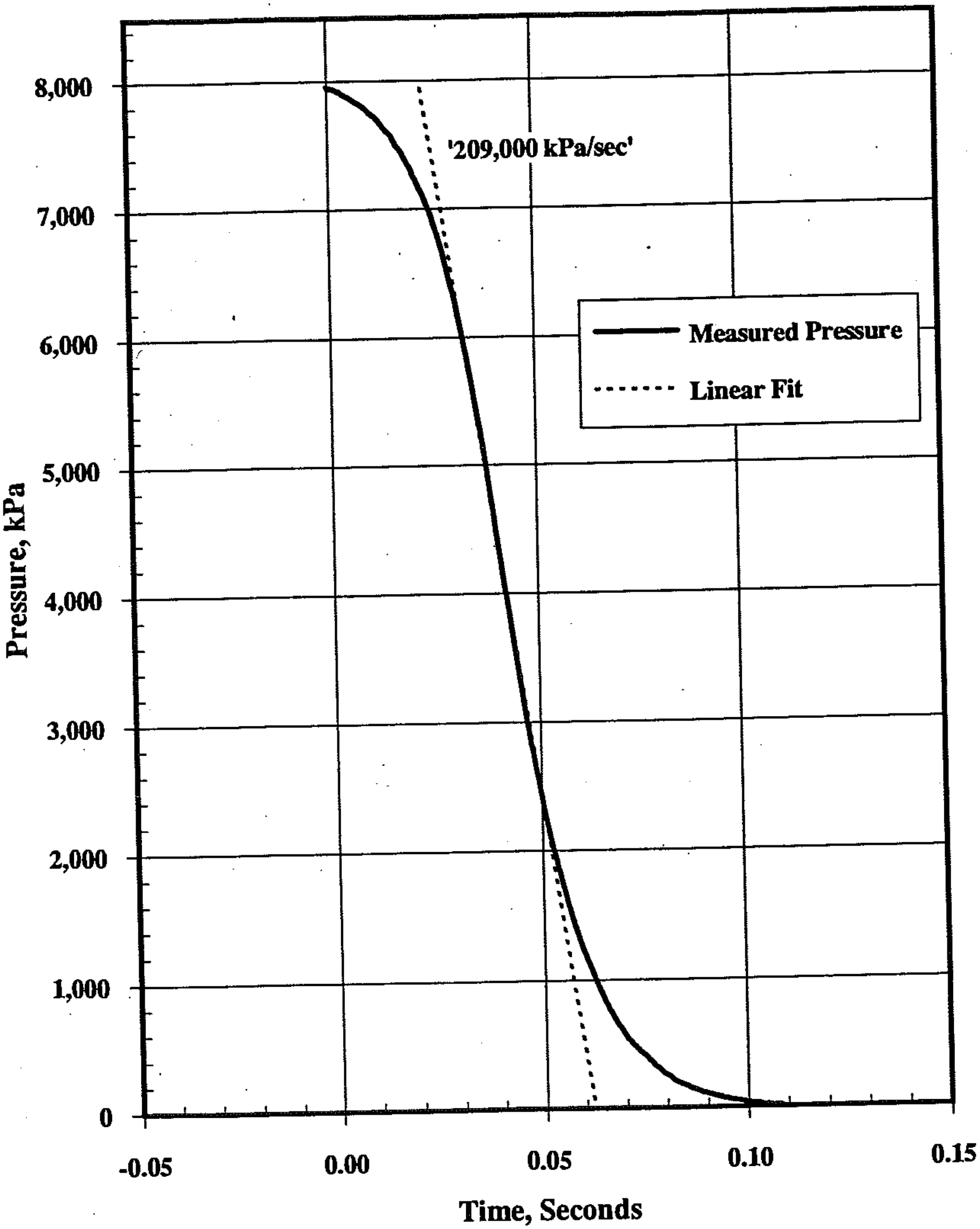

Figure A-7. Pressure-Time History for Original Apparatus.
after Janssen and Snyder [38]

pressure release rate over a similar pressure range. Also, a release rate specification and calibration procedure would be needed to verify identical performance of an alternate chamber.

A taller cylinder was obtained for the existing equipment, increasing the chamber volume by a factor of five. Because a larger volume of water would need to be released when the pressure was released (due to expansion of the larger chamber under pressure and also compression of a larger volume of water in the chamber) modifications of the valves and piping were expected. Merely increasing the test pressure did not produce the same pressure release history as the original, probably because the turbulent flow in the release path limited the rate at which the pressure could be released. Figure A-8 shows the pressure release history for the larger chamber with modifications to the valves and fittings made in order to duplicate the original pressure release rate. The pressure release histories of the original and larger chamber are very close, with a rate of 206,000 kPa/sec. (29,900 psi/sec) for the large chamber compared to the a rate of 209,000 kPa/sec. (30,300 psi/sec) for the original. (Tested with no aggregate in either chamber.) While the pressure release histories look quite alike, testing of actual aggregate specimens will be necessary to determine if similar amounts of aggregate fracturing are produced in the large chamber.

Another factor in achieving the proper release rate is speed and consistency in opening the pressure release valve. Experience with the equipment has shown that reproducible release rates are achievable after a minimal amount of practice in quickly opening the valve. While an automatic valve (solenoid, spring actuated, etc.) valve for the pressure release could improve reproducibility of the valve opening rate, such a valve has not been considered necessary. Also, discussions with a valve supplier suggest that an automatic valve would not open as quickly as a manually-operated valve.

Experience with the Washington Hydraulic Fracture Test suggests that the test procedure distinguishes between durable and non-durable aggregate pieces by fracturing

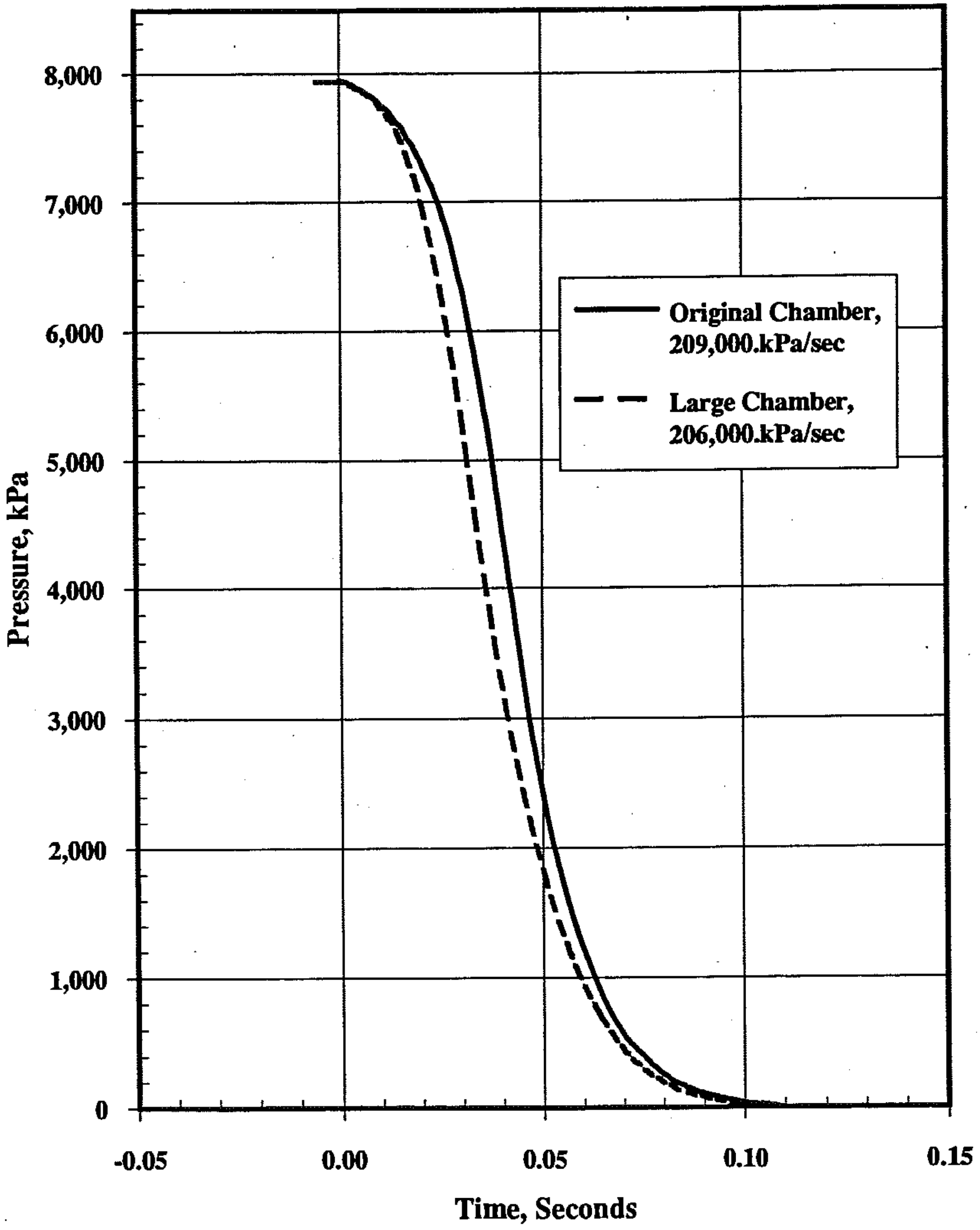

Figure A-8. Pressure-Time Histories for Original and Large Apparatus. after Janssen and Snyder [38] the non-durable pieces while leaving the durable pieces unbroken. Experience also suggests that gravel sources which typically contain a range of rock types often contain both clearly durable and clearly non-durable particles. That is, tests repeated on duplicate specimens of gravel sources usually produce substantial fracturing in the same individual rock types for that gravel source. Experience also suggests that bedrock sources, such as those that produce crushed limestone aggregate, can contain particles that are less clearly durable or non-durable. That may explain the large sample size (about 600-800 pieces) necessary to bring the coefficient of variability down to 10 percent. The consequence of these observations is that if an aggregate is used to determine if a modification to the Washington Hydraulic Fracture test equipment produces the same results, a bedrock source of marginal durability may be a better choice of test material than a gravel containing a range of rock types. A wider range of pressure release rates would probably fracture the same clearly non-durable pieces in a gravel, while a marginal bedrock source would require more exact duplication of the pressure release history in order to produce the same fracturing.

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Appendix B

WHFT Apparatus Development/Modification*

* Extracted from a Masters Thesis prepared by Thomas E. Alford, Department of Civil Engineering, University of Washington, Seattle, Washington, 1995.

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WHFT APPARATUS DEVELOPMENT/MODIFICATION

1 Introduction

A number of questions with respect to the Washington Hydraulic Fracture Test (WHFT) remained at the end of the Strategic Highway Testing Program (SHRP), including questions concerning the actual performance of the large WHFT apparatus (produced at the end of the SHRP studies but not evaluated with aggregates) and questions concerning which of the test parameters were actually critical for calibration. A testing program consisting of two phases was developed to address these questions. During the first phase, Preliminary Testing, release rate tests and aggregate tests were run in both the original SHRP apparatus and the large apparatus produced at the end of the SHRP program. The apparatus configurations were unchanged from those of the SHRP program in order to obtain a baseline from which to compare future test results. The initial pressures, however, were varied. This was done to determine whether the short duration release rate was dependent upon the initial pressure and how this affected the WHFT results.

The second phase, Apparatus Modification and Upgrading, consisted of release rate tests and aggregate tests on both the original apparatus and the large apparatus. Slight modifications to the apparatus configurations were made in order to obtain a range of short duration release rates, decrease release rate variability, or improve chamber reliability.

2 Release Rate Measurement

The release rate measurement procedure can be separated into two distinctly different tasks. The first task, data collection, was performed in a way similar to the standard aggregate testing procedure, but with slight chamber modifications and some additional required equipment. The second task, data analysis, involved taking the data collected during the data collection procedure and then producing pressure-time history curves and pressure release rate curves for the chamber configuration being tested. Pressure-time history curves show the pressure in the chamber versus time. Pressure release rate curves show the average rate at which pressure is released from the apparatus (in kPa/second) versus the duration over which the average is taken.

2.1 Data Collection

In addition to the standard WHFT apparatus, two additional systems were obtained: a pressure transducer system and a data acquisition system. The pressure transducer system consisted of a pressure transducer, its associated power supply, and signal conditioning electronics. This system was able to accurately measure the pressure within the chamber to within 3 percent over the range of zero psi to the maximum pressure measured. The pressure transducer in this work was attached at the base of the chamber on the chamber fill valve mount.

The data acquisition system consisted of equipment for digitally recording the output from the pressure transducer system. In this case, the data acquisition system consisted of a Fourier analyzer that recorded voltage output from the pressure transducer at a sampling rate of either 4,096 Hz or 2,048 Hz.

The procedure for collecting the data was the same as that for the aggregate testing. While the pressure was released from the chamber, the pressure in the chamber versus time was digitally recorded. After ten pressure releases had been recorded, one calibration run was completed, and the data were then analyzed.

2.2 Data Analysis

After the pressure time history had been digitally recorded , via the output voltage supplied by the transducer for the series of ten pressure releases, the raw data were analyzed to produce pressure release rate curves. Output voltage was converted to pressure with a calibration factor supplied with the transducer. Release rate curves showed the pressure release rate plotted against duration.

The release rate for a given duration is calculated as follows. Starting with a vary small duration (0.002 seconds), enter the pressure time history curve at time zero. Record the pressure at time zero, then record the pressure at time 0.002 seconds (0.002 seconds after the original time). Calculate the difference between the two pressures, and then divide that difference by the duration, 0.0002 seconds. This numerical result is termed the pressure release rate for that portion of the time history curve (time = 0 seconds to time = .002 seconds). Therefore, by definition, the pressure release rate for a given duration is the magnitude of the slope of a line drawn between the end data points on the pressure time history curve for that given duration. To find the maximum release rate for a given duration, calculate the pressure release rate over that duration for every data point on the pressure time history curve, and then choose the highest calculated release rate. To generate pressure release rate curves, calculate the release rate for successively longer durations and then plot the release rates versus duration. Note that the release rate curves shown in the following sections are the average of at least ten consecutive pressure releases; thus, the 0.002 second release rate was calculated for ten consecutive releases and then averaged.

A typical sampling rate between 1,000 and 4,000 hertz (2,048 Hz to 4,096 Hz in this study) will produce approximately 1,000 to 4,000 data points per pressure-time history curve. To facilitate the completion of this study, a computer program was written to mechanically perform the release rate calculations for the desired durations.

3 Preliminary Testing

3.1 Original Apparatus Release Rate

As stated above, one of the purposes of the research was to identify the important parameters necessary for calibrating the WHFT equipment. Initial test development work [1] suggested that a critical pressure-time history exists that defines the WHFT. Also, this pressure-time history seemed to be sensitive to initial chamber pressure. Measurements of the pressure-time histories for the original chamber at both 7,240 and 7,930 kPa (the standard initial pressure used in previous work) initial pressures are shown in Figure B-1. The initial pressure difference can easily be seen, but otherwise the slopes of the curves look quite similar.

The critical parameters of the pressure-time history probably consist of an initial pressure, a critical pressure release rate, and a duration for which this release rate must be maintained. To determine whether the higher initial pressure allowed a given pressure release rate to be maintained for a longer duration , the release rate versus duration relations were determined. These are shown in Figure B-2 for the initial pressures of 7,240 (two days of release rate testing for the average of 20 releases) and 7,930 kPa (ten days of release rate testing for the average of 100 releases). The use of the lower pressure (7,240 kPa) resulted in lower pressure release rates for all durations.

3.2 Large Apparatus Release Rate

The SHRP program [2] developed a large WHFT apparatus that produced similar, but not exact, pressure-time histories. Calibration tests were run on both the original WHFT apparatus and the large apparatus. The pressure release rate results are shown in Figure B-3. It can be clearly seen that the large chamber gave consistently low release rates for an initial pressure of 7,930 kPa (one day of release rate testing for the average of ten) for durations of up to about 0.07 sec.. Calibration tests were also run on the large

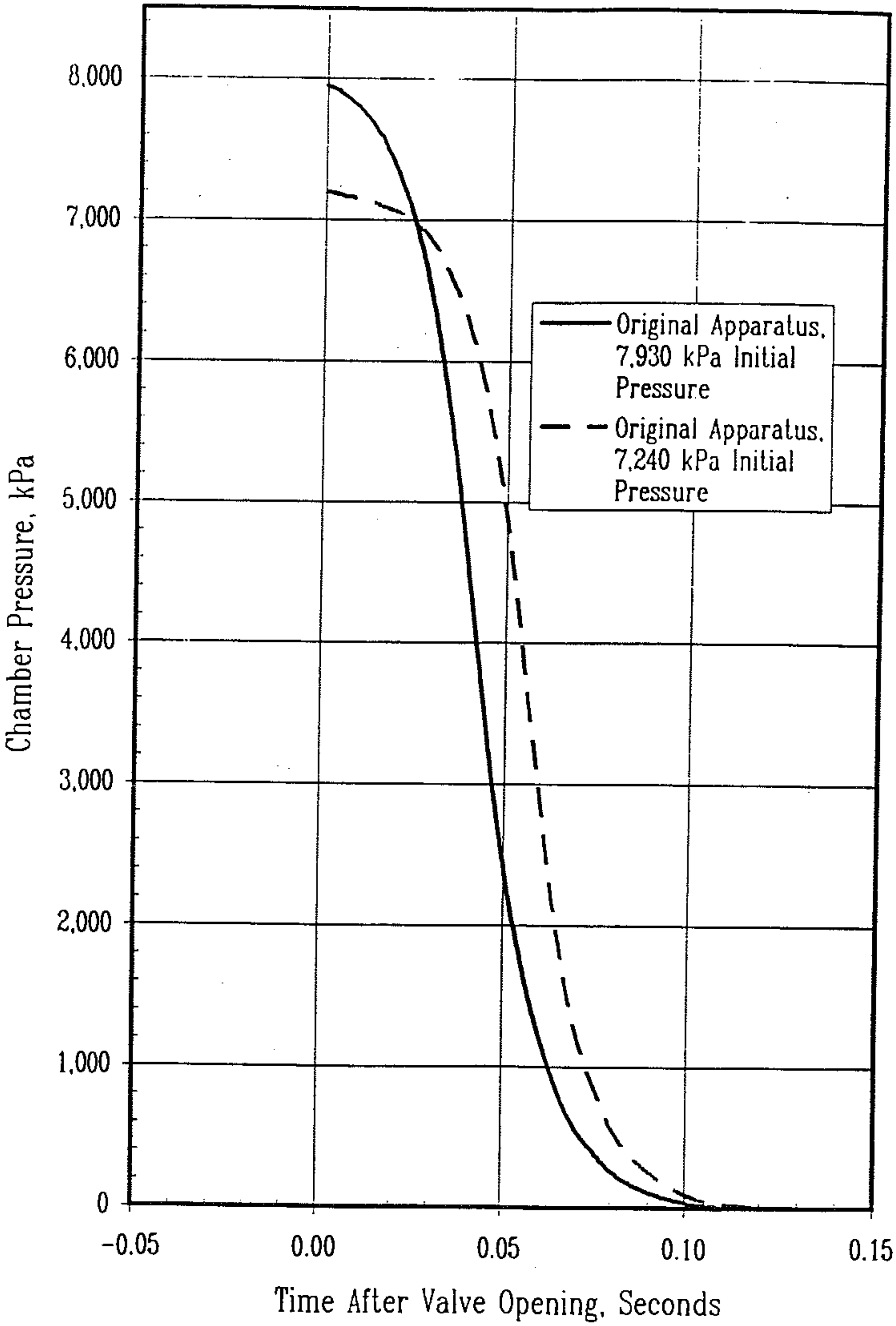


Figure B-1. Pressure Release Histories for Original Apparatus at both 7,240 and 7,930 kPa Initial Pressures

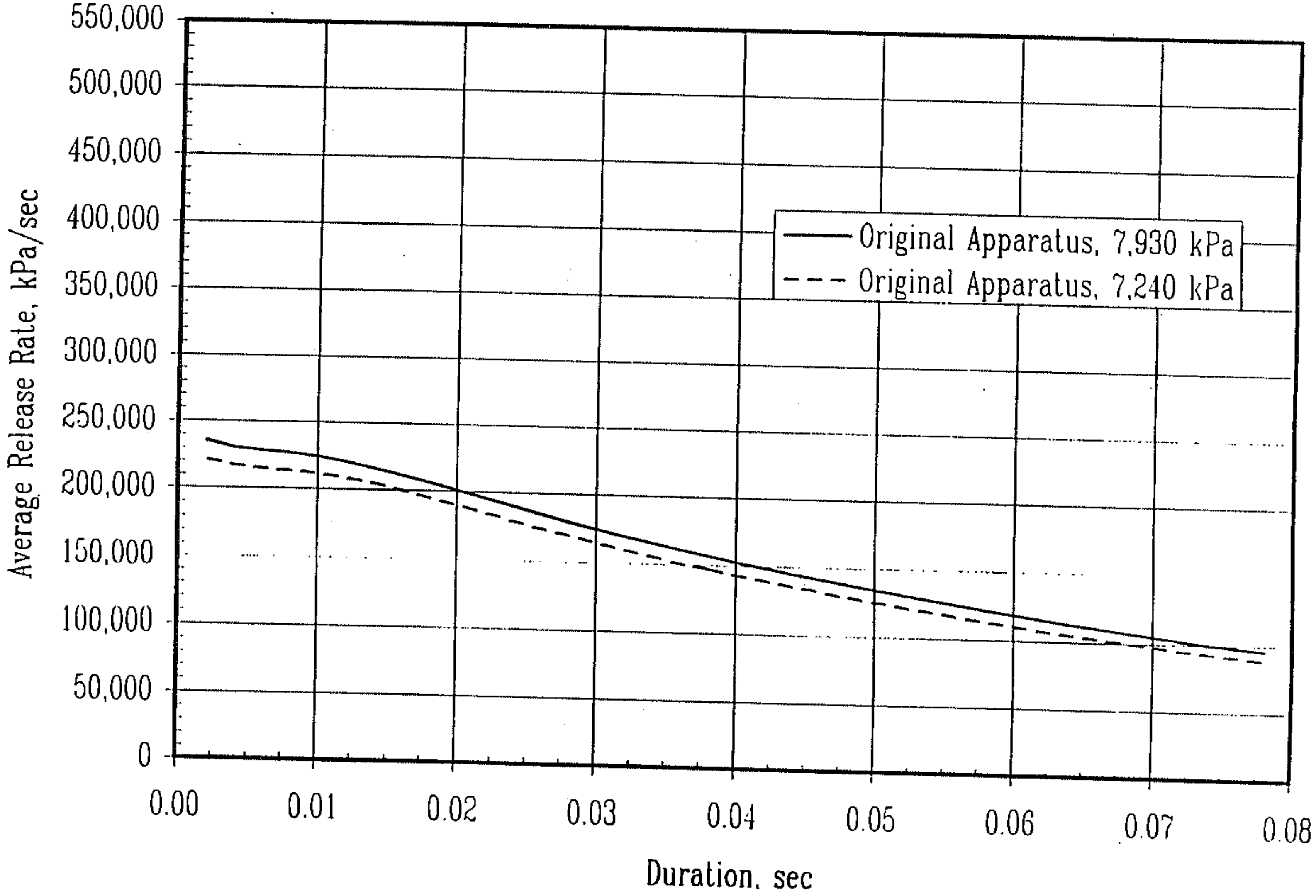


Figure B-2. Pressure Release Rates for the Original Apparatus at both 7,240 and 7,930 kPa Initial Pressures

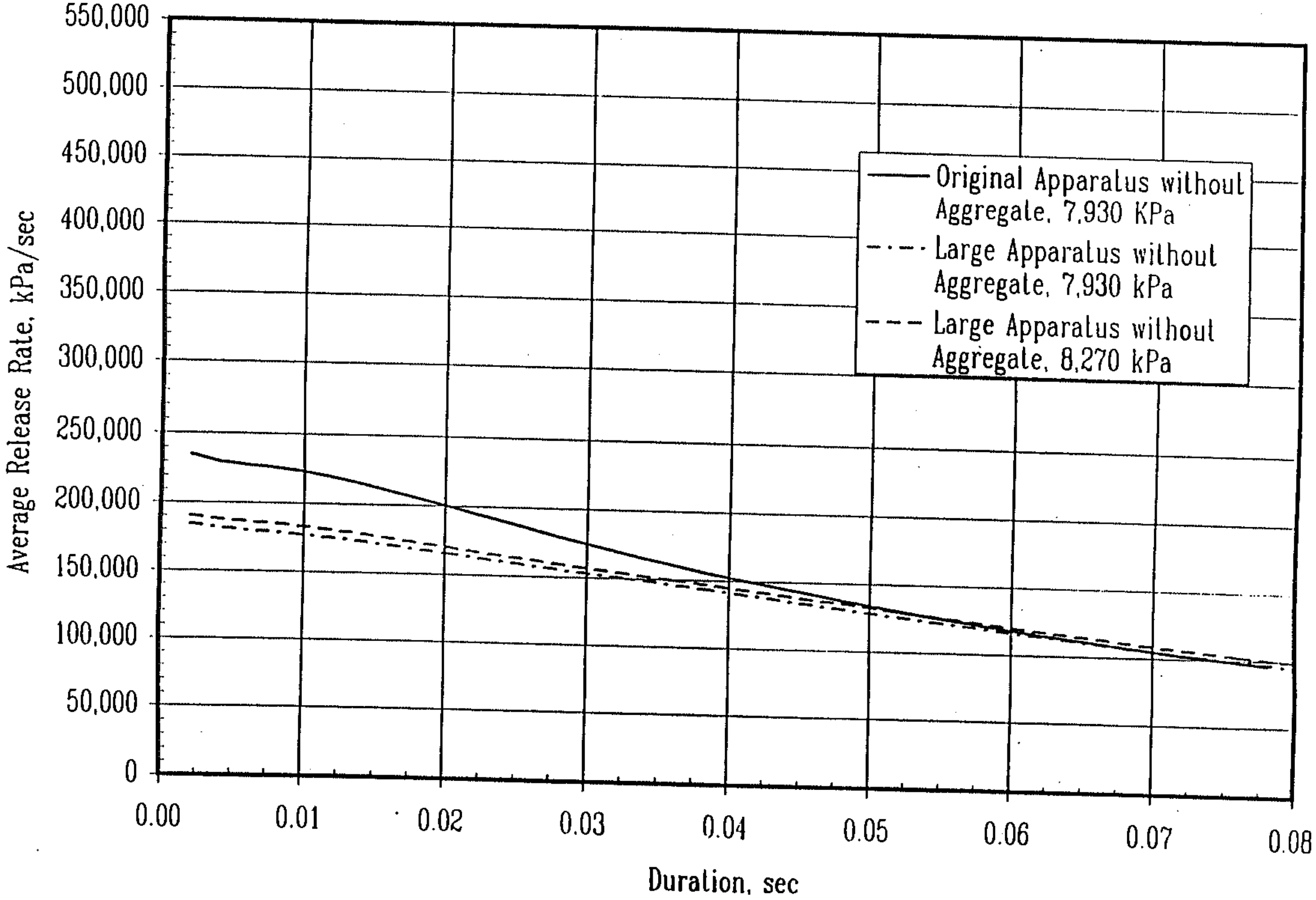


Figure B-3. Pressure Release Rates for the Original and Large Apparatus

apparatus using an initial pressure of 8,270 kPa (two days of release rate testing for the average of 20 releases) to determine whether this improved the pressure release rate. This result is also shown in Figure B-3. Although the pressure release rate increased slightly, it did not increase to the level of the release rate for the original apparatus at the standard 7,930 kPa initial pressure until the duration exceeded about 0.05 seconds.

Release rates for the large apparatus at higher initial pressures were analyzed, but these were also low at short durations in comparison to the release rate of the original chamber. This suggested that the large chamber configuration had reached the maximum release rate possible with the existing fitting and valve configuration.

3.3 Effect of Aggregate in the Apparatus on Pressure Release Rate

Early in the preliminary testing stage of this work a question arose regarding the possible effects of the presence of aggregate on the release rate. If there were no effect, the initial calibration could be limited to one day of testing, and then the release rate could be continuously monitored (and adjusted if necessary) throughout a WHFT series.

To determine this effect, pressure-time histories were recorded during actual aggregate tests, and release rate curves were created from the results. The results of this testing can be seen in Figures B-4 and B-5. The 95 percent confidence intervals for the apparatus configurations are also plotted on the figures. As the figures show, the release rates for both the large and original apparatus with and without aggregate were very close. At a duration of 0.01 seconds, the release in the original apparatus decreased 4.7 percent with the addition of the aggregate. The release rate for the large apparatus increased 6.3 percent at the 0.01 second time interval with the addition of the aggregate. Both these variations seemed to be insignificant.

To aid in determining whether these results were in fact insignificant, 95 percent confidence intervals were developed for each of the scenarios in question: the original

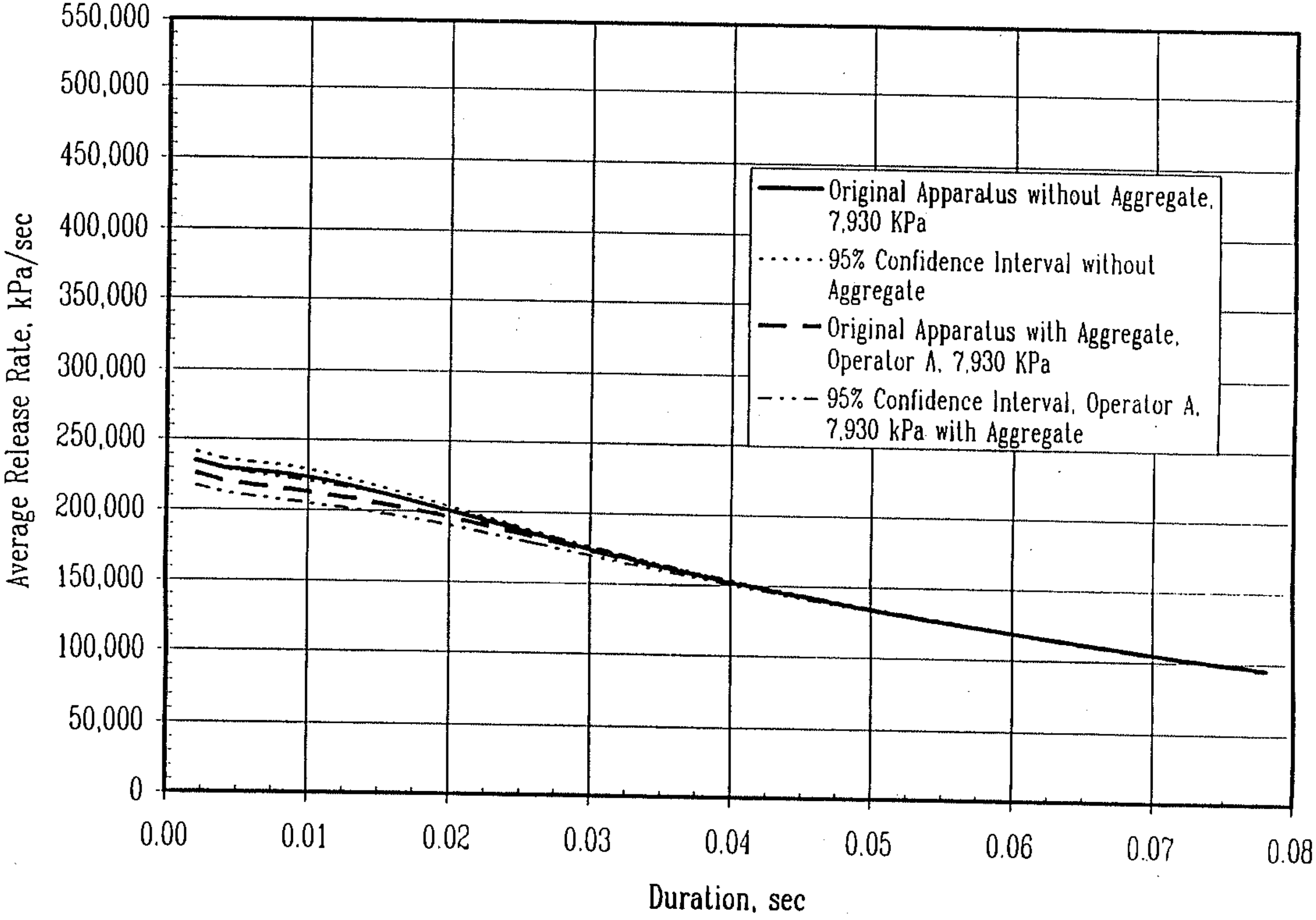


Figure B-4. Pressure Release Rates and 95 Percent Confidence Intervals for the Original Apparatus, With and Without Aggregate

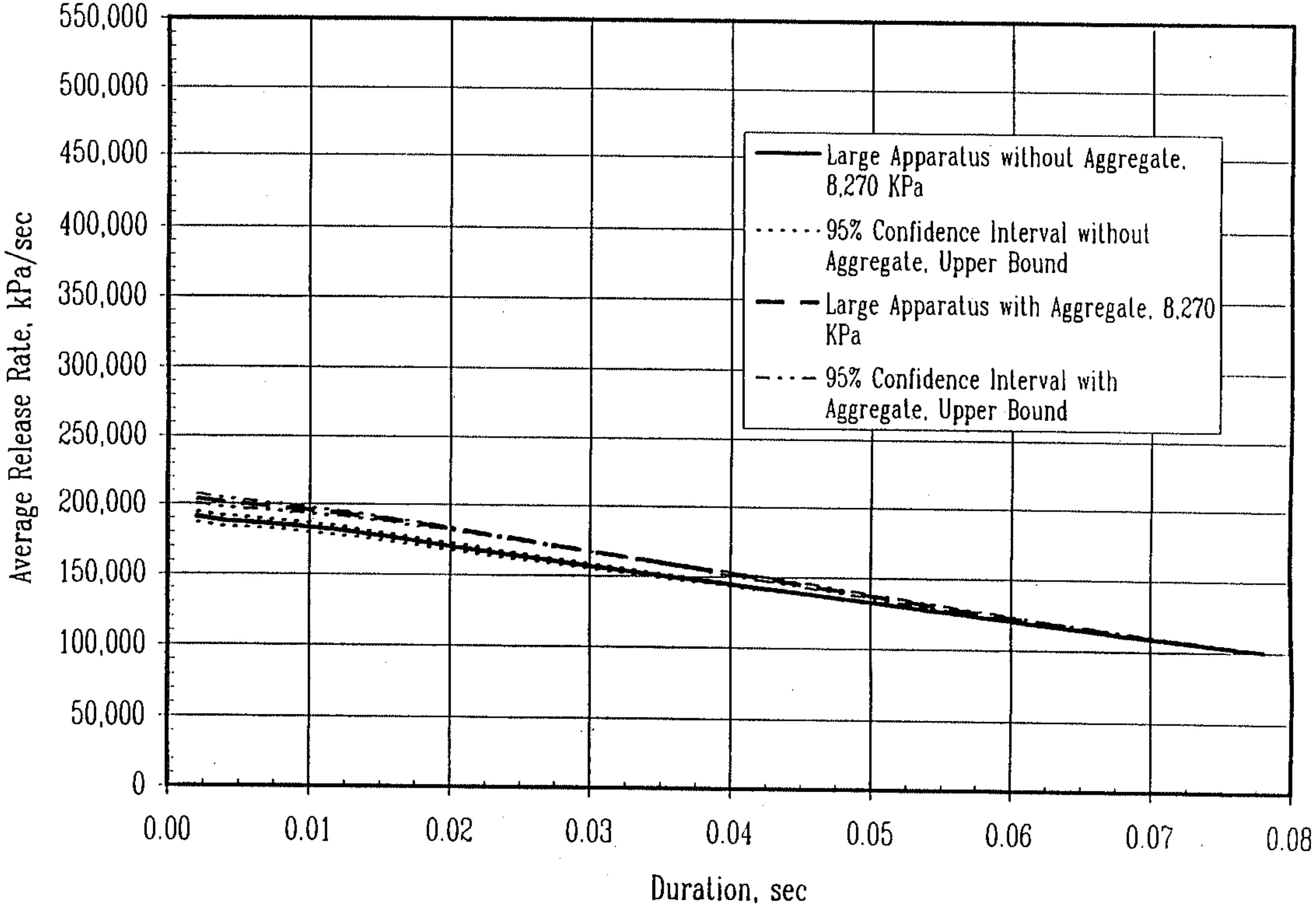


Figure B-5. Pressure Release Rates and 95 Percent Confidence Intervals for the Large Apparatus, With and Without Aggregate

apparatus with aggregate, the original apparatus without aggregate, the large apparatus with aggregate, and the large apparatus without aggregate. The upper and lower bounds of these confidence intervals can be seen on Figures B-4 and B-5. For the large apparatus, the confidence intervals are very tight around each release rate average (with and without aggregate). This indicates that the difference between the two release rates is significant. The release rate increased with the addition of aggregate in the large apparatus, whereas it decreased with the addition of aggregate in the original apparatus. This indicates that aggregate in the chamber has no consistent effect on release rate.

The confidence intervals for the original apparatus are not nearly as tight around the average release rate as those for the large apparatus. In fact, the confidence intervals overlap, indicating that there is no significant difference between the two scenarios. In some respect the increased variability is surprising, because the release rates shown for both the tests with and without aggregate are the average of ten days of testing. This difference in release rate variability between the large and original apparatus may be the result of a difference in the pressure release valve. The large apparatus had a 9.5-mm ball valve through which the chamber pressure was released. This type of valve had a 125-mm long handle that allowed fast, smooth operation. The original apparatus had a 9.5-mm plug valve for a pressure release valve. This valve had a short handle that was prone to sticking and that wore out quickly from the repeated use that it was subjected to in this research. Also, the lack of a long lever arm (no handle) on the plug valve seemed to lead to a greater likelihood of operator-induced variability in the release rate .

In general, the results of the testing and analysis revealed that it is not necessary to have aggregate in the chamber to carry out the calibration procedure. What seemed to be of more interest was the variability associated with the use of the plug valve, indicating that steps should be taken to increase the reliability of the chamber by decreasing operator-induced variability in the release rate.

3.4 Operator Induced Release Rate Variability

As mentioned above, tests produced some concern regarding the effect of different operators on the release rate of the original apparatus. To determine the significance of operator-induced release rate variability, release rate testing was conducted on the original apparatus with aggregate in the chamber by two different operators. The two operators are referred to as Operator A and Operator B. For the variability tests, each operator collected release rate data for ten days. The release rates for each of the ten days were then calculated and averaged. The averages, along with the 95 percent confidence interval, were then plotted. The results of this can be seen on Figure B-6. The figure clearly shows that the release rate for Operator B was significantly below that for Operator A (approximately 20 percent at a duration of 0.01 seconds). This indicated that aggregate testing in the original apparatus should be conducted by the same operator and that the apparatus should be calibrated separately for each operator if release rate has a significant effect on HFI.

3.5 Rubber Lining of Chamber

During the course of this research, certain aggregate pieces tested in the original apparatus were found to have been fractured in a manner that more resembled crushing in compression than hydraulic fracture. Fractures caused by the hydraulic fracture mechanism are generally characterized by random and erratic fracture faces. It is easy to imagine that this fracture pattern is the result of internal forces pushing outward on the aggregate. Crushing in compression looks significantly different. The fracture pattern originates at a point on the surface of the aggregate piece where it was in contact with the apparatus lid. The fractures radiate outward from this point. Also, at the point of contact between the aggregate and the lid, the aggregate piece exhibits a disfigurement that resembles a dimple on a golf ball. The dimple is filled with finely crushed particles, similar to sand, that used to be part of the composite aggregate piece. Flat planar pieces or

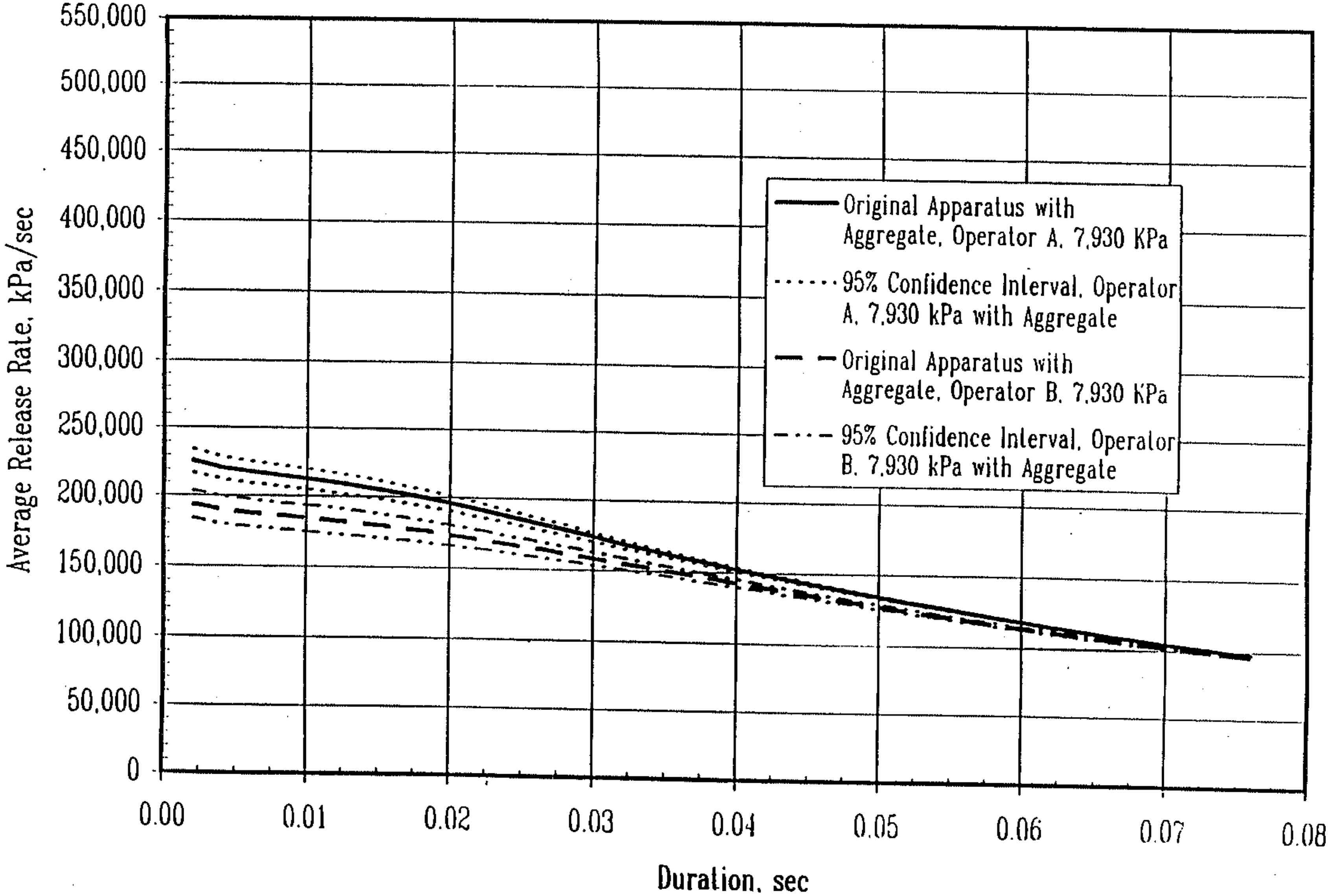


Figure B-6. Pressure Release Rates and 95 Percent Confidence Intervals for the Original Apparatus with Aggregate, Operator A versus Operator B

elongates can also be broken in flexure. These pieces do not portray a radial fracture pattern, but rather appear to be broken in bending. This type of fracturing is characterized by smooth fracture planes.

The aggregate compression or bending failures are theorized to have occurred when the apparatus chamber expanded and then contracted. The chamber could expand upon pressurization, and the aggregate would settle into the newly created volume. When the pressure was released, the chamber would contract back to its original dimensions, placing compressive forces on the newly settled aggregate. It must be recognized, however, that regardless of how high the compressive forces, aggregate can not be crushed if the aggregate is not compressed beyond a critical strain value. The amount to which the aggregate can be strained is dependent on the relative displacement of the apparatus lids.

To validate the theory that aggregate was being fractured by crushing and bending mechanisms, a structural analysis was completed on the original apparatus. In this analysis, the relative displacement between the apparatus lids was assumed to occur in two ways: by stretching the bolts that held the apparatus lids together and by bending the lids outward. The total relative displacement would be the sum of the two.

The displacement of the lids due to the bolt stretch is summarized by the following equation:

$$\delta = PL/EA \qquad \text{(Eq. B-1)}$$

where: δ is the magnitude of bolt stretch (in.)

P is the total force on the bolts (pounds)

P is given by:

$$P = ((\pi \times r^2)/2) \times q_o \qquad \text{(Eq. B-2)}$$

where: r is the radius of plate upon which the load acts (in.)

q_o is the uniform distributed load (psi)

A is the total area of the bolts (in.^{2})

A is given by:

$$A = n\times(\pi\times d^2)/4 \qquad \text{(Eq. B-3)}$$

where: n is the number of bolts

d is the bolt diameter (in.)

The outward deflection of the chamber lids can be calculated on the basis of either of two initial assumptions. The first is that the lids' edge connection is a pin connection. The second is that the lids' edge connection is a rigid connection. In reality, given that the lids are constrained by sixteen bolts at their edge, the actual deflection of the lids will fall somewhere between the above two deflections. Although the total deflection of the apparatus will fall somewhere between that of a rigidly connected plate and a pin connected plate, it will act more like a pin connected plate. This is because the bolt holes have a diameter larger than that of the bolt, and the area of contact between the bolt head and the apparatus lid is routed to form a smooth curving contact plane. The total relative displacement between the lids is equal to twice the deflection of one of the lids because of the distributed load. The maximum deflections (the deflections at the center of the lid) for the above assumptions are given by the following equations: [3]

Simply supported edge:

$$\omega_0 = q_o a^4/32D[(3+\nu)/(1+\nu) + 1/2] \qquad \text{(Eq. B-4)}$$

Fixed edge:

$$\omega_0 = q_o a^4/64D \qquad \text{(Eq. B-5)}$$

where: ω_0 is the out of plane displacement at center of plate (in.)

a is the radius to connection (in.)

ν is Poisson's Ratio (0.295 assumed for steel)

$$D = Eh^3/12(1-\nu^2) \qquad \text{(Eq. B-6)}$$

where: E is Young's Modulus (29×10^6 psi for steel)

h is the plate thickness (in.)

The above equations assume that the distributed load is applied over the entire area out to the connections. In the case of the original apparatus, the bolted connection occurred at a radius of 152 mm. The load, however, was only applied to a radius of 133 mm. Also, given that the lids behave more like a pin-connected plate than a rigidly connected plate, but that the pin-connected assumption would overestimate the actual deflection, the 133-mm radius was used.

A summary of the relative displacement at the center of the lids is given in the following table for a range of initial pressures.

Table B-1: Summary of Relative Displacements at Center of the Apparatus Lids

Apparatus Pressure	Bolt Stretch	Relative Displacement Assuming Pin Connection	Relative Displacement Assuming Rigid Connection	Relative Displacement Range
1,050 psi (7,240 kPa)	9.05×10^{-4} in. (2.30×10^{-2} mm)	0.057 in. (1.46 mm)	0.019 in. (0.478 mm)	0.020-0.058 in. (0.501-1.48 mm)
1,150 psi (7,930 kPa)	9.91×10^{-4} in. (2.52×10^{-2} mm)	0.063 in. (1.60 mm)	0.021 in. (0.524 mm)	0.022-0.064 in. (0.549-1.62 mm)
1,250 psi (8,620 kPa)	1.08×10^{-4} in. (2.74×10^{-2} mm)	0.068 in. (1.73 mm)	0.022 in. 0.567 mm)	0.024-0.069 in (0.597-1.76 mm)

As can be seen from the table, the maximum relative displacement can be as great as 1.8 mm. This is enough to account for the unusual fracturing that occurred. To mitigate this situation, an 0.8-mm (1/32-in) neoprene pad was attached to both the top and bottom apparatus lids. This appeared to eliminate the majority of the non-hydraulic fracturing that was occurring. The decrease in fracturing can be seen in the following table, which shows percent fractures for a Michigan limestone both before and after the neoprene pad was added to the apparatus.

Table B-2: WHFT Percent Fracture Results for a Michigan Limestone, Before and After Neoprene Pad was Attached

WHFT Percent Fracture Results for a Michigan Limestone		
Chamber Configuration	**Before Neoprene Pad**	**After Neoprene Pad**
Original Apparatus 7,930 kPa	7.44	2.41
Upgraded Original Apparatus 7,240 kPa Chamber Pressure, 550 kPa Actuator Pressure	8.11	1.40

Table B-2 shows that the percent fracture was decreased substantially by the addition of the neoprene pad. Although the majority of the irregular fracturing was eliminated by the addition of the pad, an occasional fracture remained that appeared to be suspect. However, no additional steps were taken to eliminate the remaining occasional random fracture caused by the chamber expansion and contraction.

3.6 Preliminary WHFT Results

If the WHFT mechanism is in fact partly dependent upon the pressure release rate, as suggested by previous work in which the reduced fracturing corresponded to the lower release rate shown in Figure B-2, a low release rate for the large apparatus would result in a smaller percentage of fracturing in the aggregate sample. To determine whether this were the case, aggregate was tested in the large apparatus with an initial pressure of 8,270 kPa and in the original apparatus at the standard initial pressure of 7,930 kPa. The aggregate testing conducted in the original apparatus was done by Operator B. The results of the aggregate testing, in the form of percent fracture versus cycles, are shown in Figure B-7. As can be seen on the figure, the percent fractures for the two scenarios were nearly identical. In an attempt to explain this, release rate curves were calculated from the pressure time-histories that were recorded during aggregate testing. The results of this effort can be seen in Figure B-8. The figure shows that the release rate for the original apparatus was not higher than that for the large apparatus but was approximately 8 percent

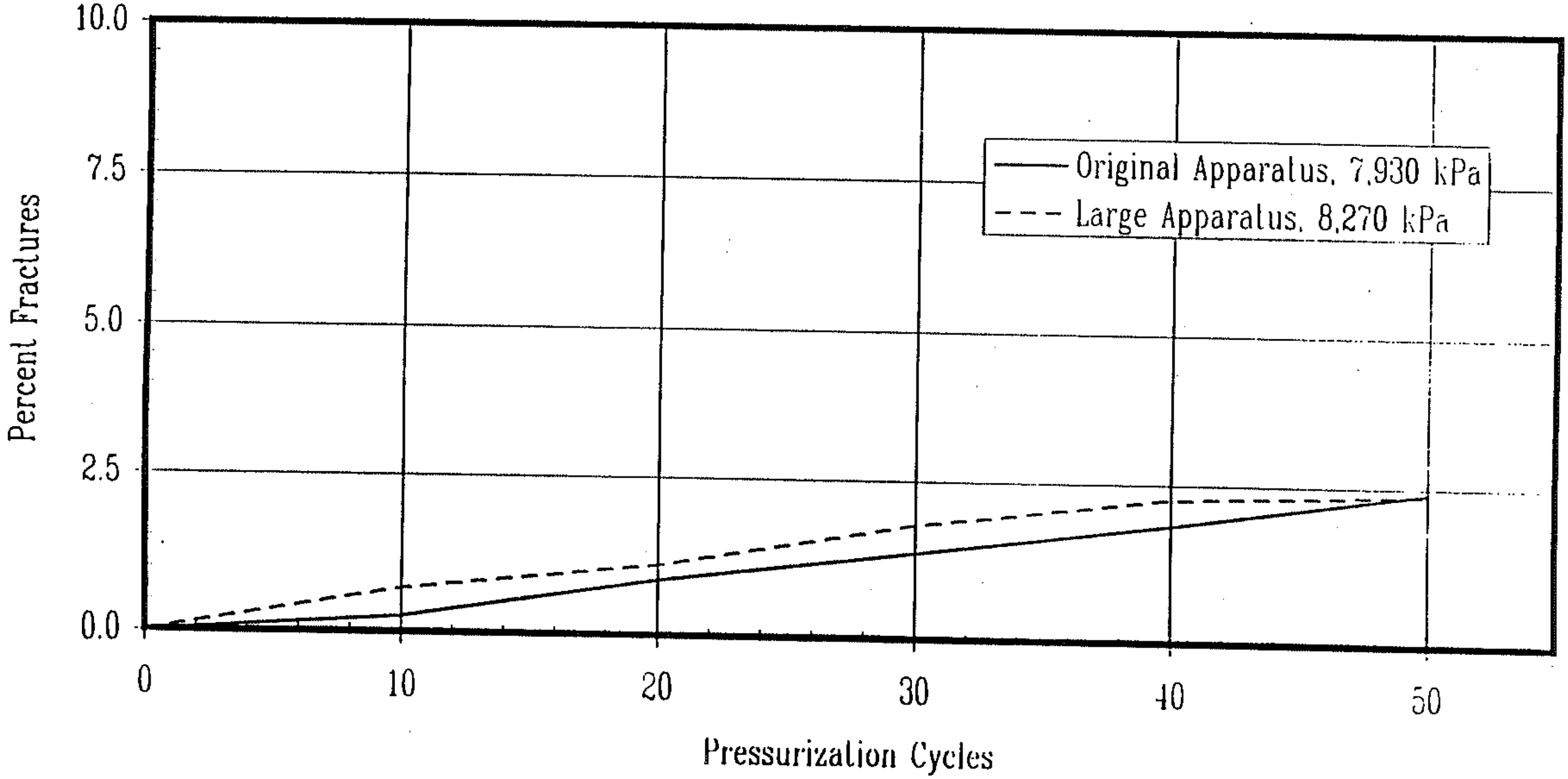


Figure B-7. Percent Fracture versus Number of Cycles for Original and Large Apparatus

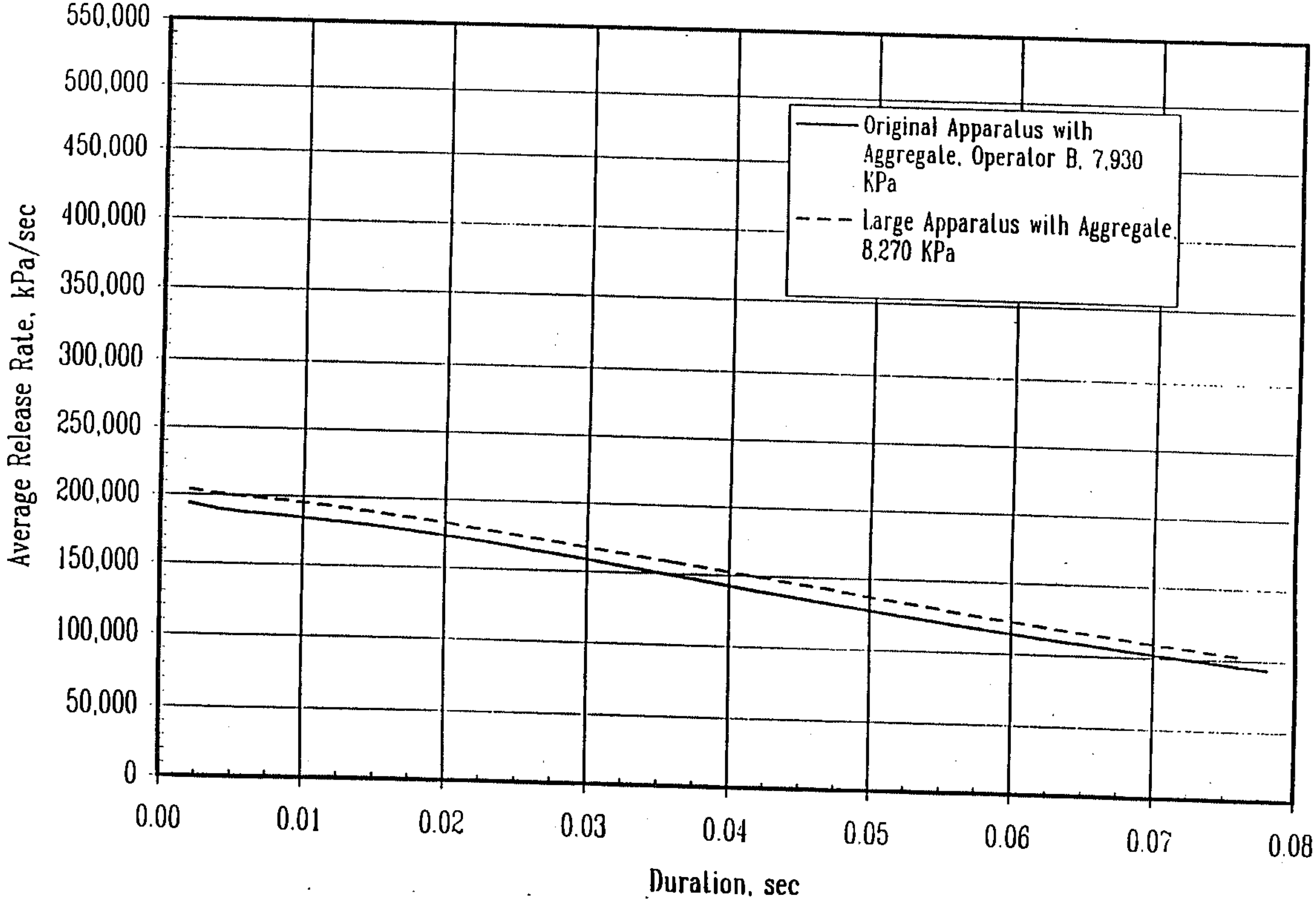


Figure B-8. Pressure Release Rates for the Original and Large Apparatus

apparatus was not higher than that for the large apparatus but was approximately 8 percent lower (calculated for a 0.01 second duration). This would explain why the percent fractures were similar. The slight increase in apparatus pressure from the original to the large apparatus did not seem to have an effect on the final percent fracture, although the large apparatus did have more fracturing for cycles 10 through 40.

4 Apparatus Modification and Upgrading

In an attempt to test the hypothesis that release rate, release rate duration, and initial pressure were the key parameters in defining the WHFT, the two chambers, original and large, were modified. The modifications were intended to either produce a range of release rates and release rate durations, decrease release rate variability, or improve the apparatus reliability.

Two primary modifications were made, one to the large apparatus and one to the small apparatus. The modification to the large apparatus consisted of upgrading the pressure release valve and associated piping by increasing the valve bore diameter and piping diameter. The modification to the original apparatus consisted of upgrading the valve system by replacing the plug valve with a ball valve and attaching an electro-pneumatic actuator to the pressure release valve.

4.1 Large Apparatus Modification

As mentioned above, the large apparatus appeared to be limited in terms of achievable release rate by its fitting and valve configurations. To increase the release rates in the large apparatus the fluid flow resistance was reduced by replacing the existing 9.5-mm pressure release ball valve with a 19-mm ball valve. Also, the associated piping was increased from 9.5-mm to 13-mm in diameter. (This new large apparatus is hereafter referred to as the "modified large apparatus.") Calibration testing was then conducted on the modified large apparatus at initial pressures of 7,930 and 8,270 kPa.

4.2 Original Apparatus Modification

During testing with the original chamber, problems with maintenance of the pressure-release valve were encountered. As mentioned earlier, this valve was a plug-type valve with O-ring seals that frequently required replacing. Also, operator-induced release rate variability was a concern with the use of the plug valve. Therefore, the plug-type valve was replaced with a ball-valve that had a larger internal bore and better reliability. Also, an electro-pneumatic actuator was added to the pressure release ball valve. The purpose of this addition was primarily to decrease operator-induced release rate variability, but it also had the effect of dramatically increasing the release rate. This increase was due to the fact that the actuated valve was able to open much faster than a hand turned valve. The original apparatus with the ball valve and electro-pneumatic actuator will be referred to as the "upgraded original apparatus".

The release rate of the upgraded original apparatus was varied by changing the initial pressure and the input pressure to the pneumatic portion of the actuator. Calibration testing was conducted on the upgraded original apparatus at initial pressures of 7,240 kPa chamber pressure and 480 kPa actuator input pressure (7,240 chamber pressure/480 kPa actuator pressure), then 7,240/550 kPa, 7,930/590 kPa, 8,620/550 kPa, and 8,620/620 kPa. Release rate data were also collected during aggregate testing. They were collected to verify the calibration results, as the original apparatus appeared to produce more variation, with and without aggregate, than the large apparatus. Testing for variability between operators was not conducted on the upgraded original apparatus, as the pressure release valve was opened via an electronic switch, which was unlikely to operate differently on the basis of the operator.

4.3 Aggregate Testing

Aggregate testing with the above configurations was also conducted. Testing in the modified large apparatus consisted of a single specimen of at least 800 pieces for each initial pressure, 7,930 kPa and 8,270 kPa. Testing in the upgraded original chamber was conducted at 7,240/550 kPa, 7,930/590 kPa, and 8,620/620 kPa. Testing at 7,240/550 kPa consisted of four specimens; testing at 7,930/590 kPa consisted of three specimens; and testing at 8,620/620 kPa consisted of two specimens. Each specimen consisted of approximately 200 aggregate pieces. The results of the replicate specimens were combined for presentation of the results. Also, release rate data were collected during aggregate testing for the upgraded original apparatus. This was done to verify that the limited number of calibration runs was producing reliable release rate results.

5 Pressure Release Rate Results

5.1 Modified Large Apparatus Release Rate Results

The results of the modified large apparatus calibration tests, without aggregate, can be seen in Figure B-9. The original apparatus release rate curve, with aggregate, is also shown for comparison. Release rate testing for the large apparatus was not done, as previous results showed that there was very little variation in release rate due to the presence of aggregate in the chamber. As can be seen, the short duration release rates for the modified large apparatus increased. The short duration release rate (calculated at 0.01 seconds) for the modified large apparatus was approximately 20 percent higher than the short duration release rate for the large apparatus. Figure B-9 also shows that the release rate versus duration curves for the modified large apparatus follow nearly identical paths at short durations. This suggests that the maximum release rate attainable for this configuration, as limited by turbulent flow through the pressure release piping and valving, was achieved.

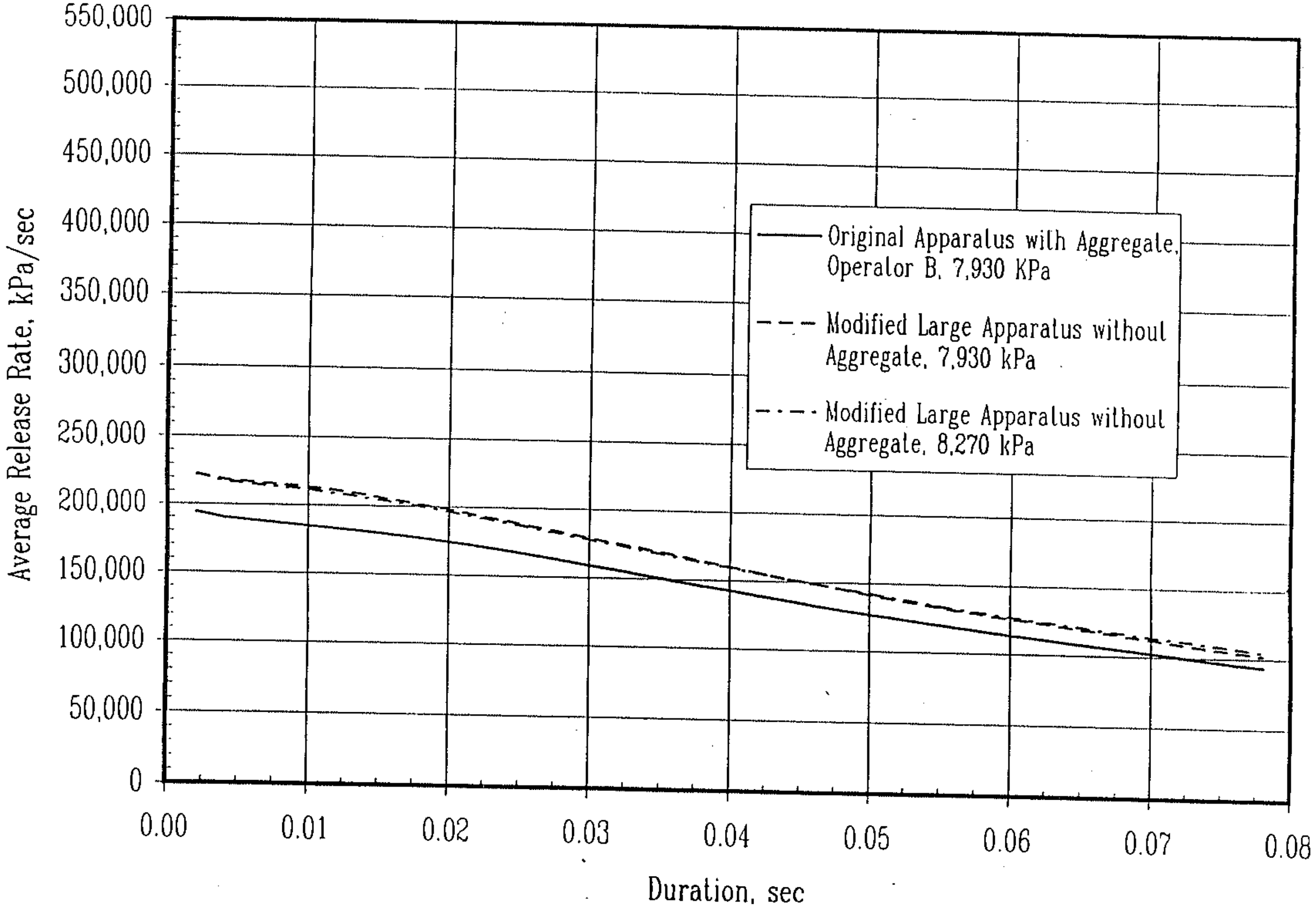


Figure B-9. Pressure Release Rates for Original Apparatus with Aggregate and Modified Large Apparatus without Aggregate

5.2 Upgraded Original Apparatus Release Rate Results

Upgraded Original Apparatus Calibration Release Rate Results

The release rate results for the upgraded original apparatus with an initial chamber pressure of 7,240 kPa are shown in Figure B-10. The release rate curve for the original apparatus with aggregate as tested by Operator B is also shown for comparison. Operator B conducted the aggregate testing in the original apparatus. The figure shows that the release rates for the upgraded original apparatus at 7,240/550 kPa and 7,240/480 kPa were above those of the original apparatus for durations of less than approximately 0.065 to 0.07 seconds.

The release rate results for the upgraded original apparatus at 7,930/590 kPa are shown on Figure B-11, along with the pressure release rate for the original apparatus with aggregate at 7,930 kPa for comparison. As can be seen, the release rate for this scenario was above that for the original apparatus at all durations.

The release rate results for the upgraded original apparatus with an initial chamber pressure of 8,620 kPa are shown in Figure B-12. The pressure release rate curve for the original apparatus with aggregate at the standard initial pressure is also shown for comparison. The two initial conditions tested were 8,260/550 kPa and 8,260/620 kPa. The release rates for these two conditions were higher than that for the original apparatus for all durations shown.

In general, the upgraded original apparatus tended to have higher release rates. This was probably due to the bore of the ball-valve, which was larger than that of the plug-valve on the original apparatus, and to the small amount of time required to open the valve because of the actuator.

Furthermore, the release rates for the 7,240/550 kPa and 8,620/550 kPa initial conditions were nearly the same for short durations, but for longer durations the 8,620/550 kPa condition maintained a faster release rate. This can be clearly seen on Figure B-13.

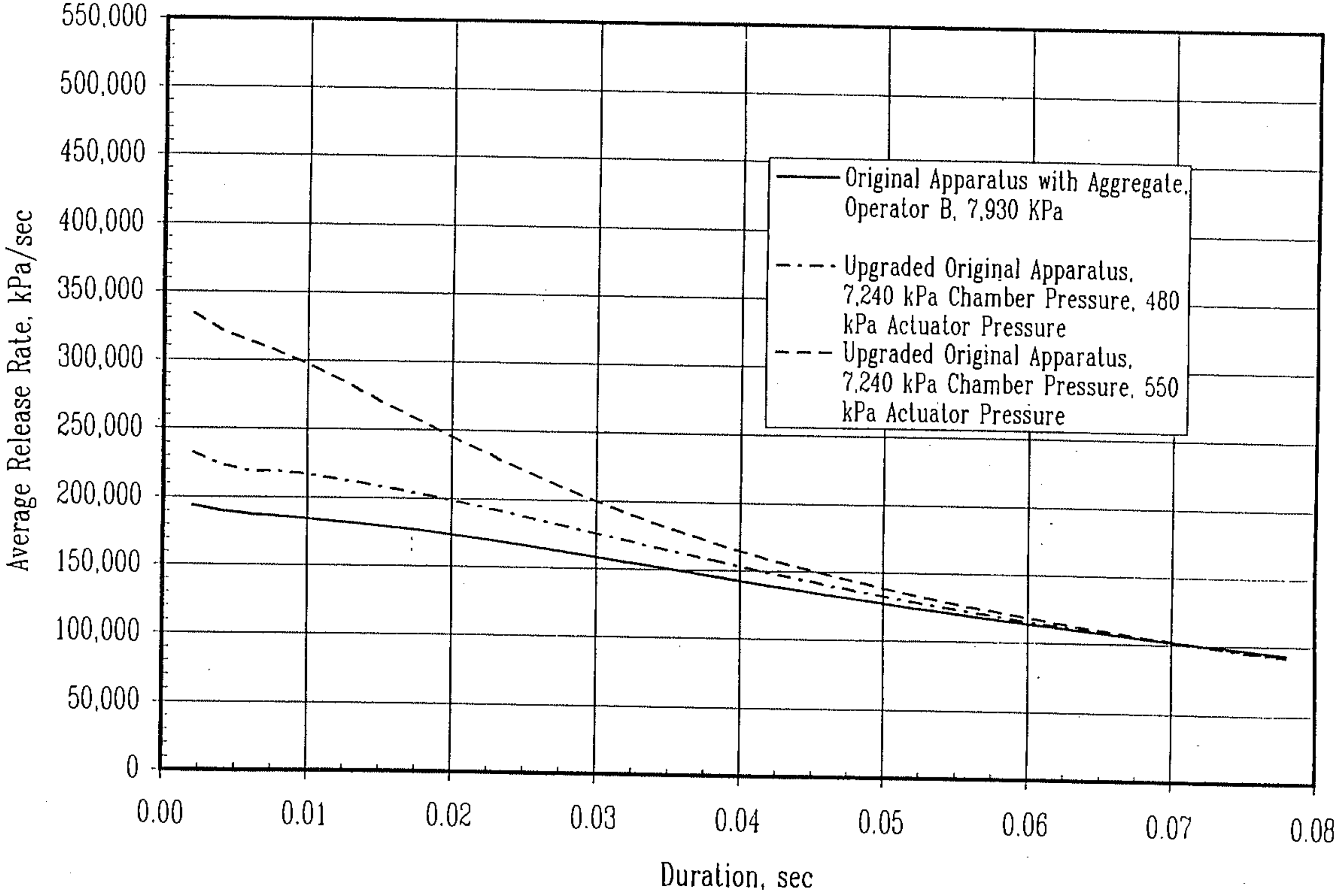


Figure B-10. Pressure Release Rates for the Original Apparatus with Aggregate and the Upgraded Original Apparatus without Aggregate at 7,240 kPa Initial Chamber Pressure

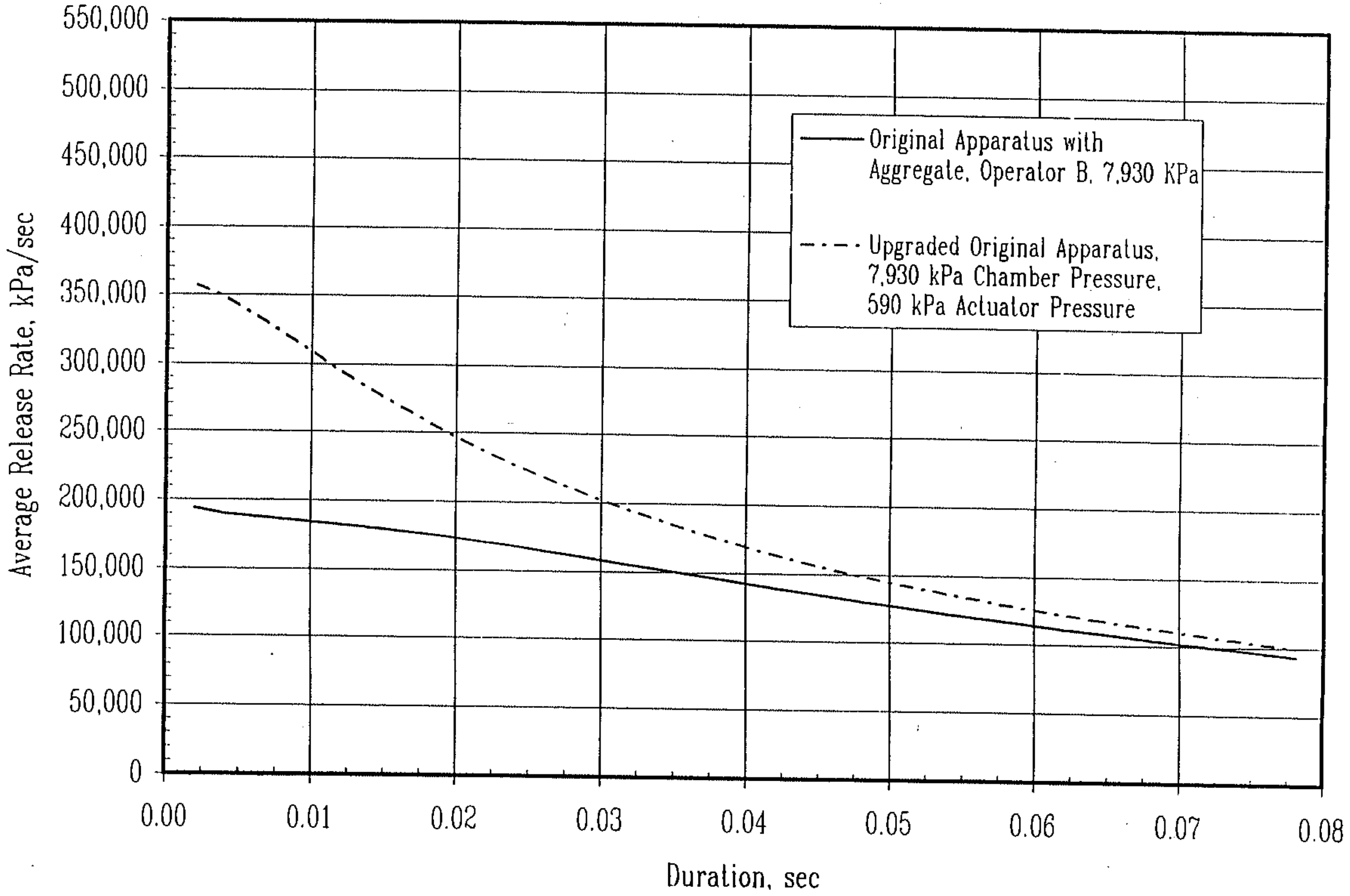


Figure B-11. Pressure Release Rates for the Original Apparatus with Aggregate and the Upgraded Original Apparatus without Aggregate at 7,930 kPa Initial Chamber Pressure

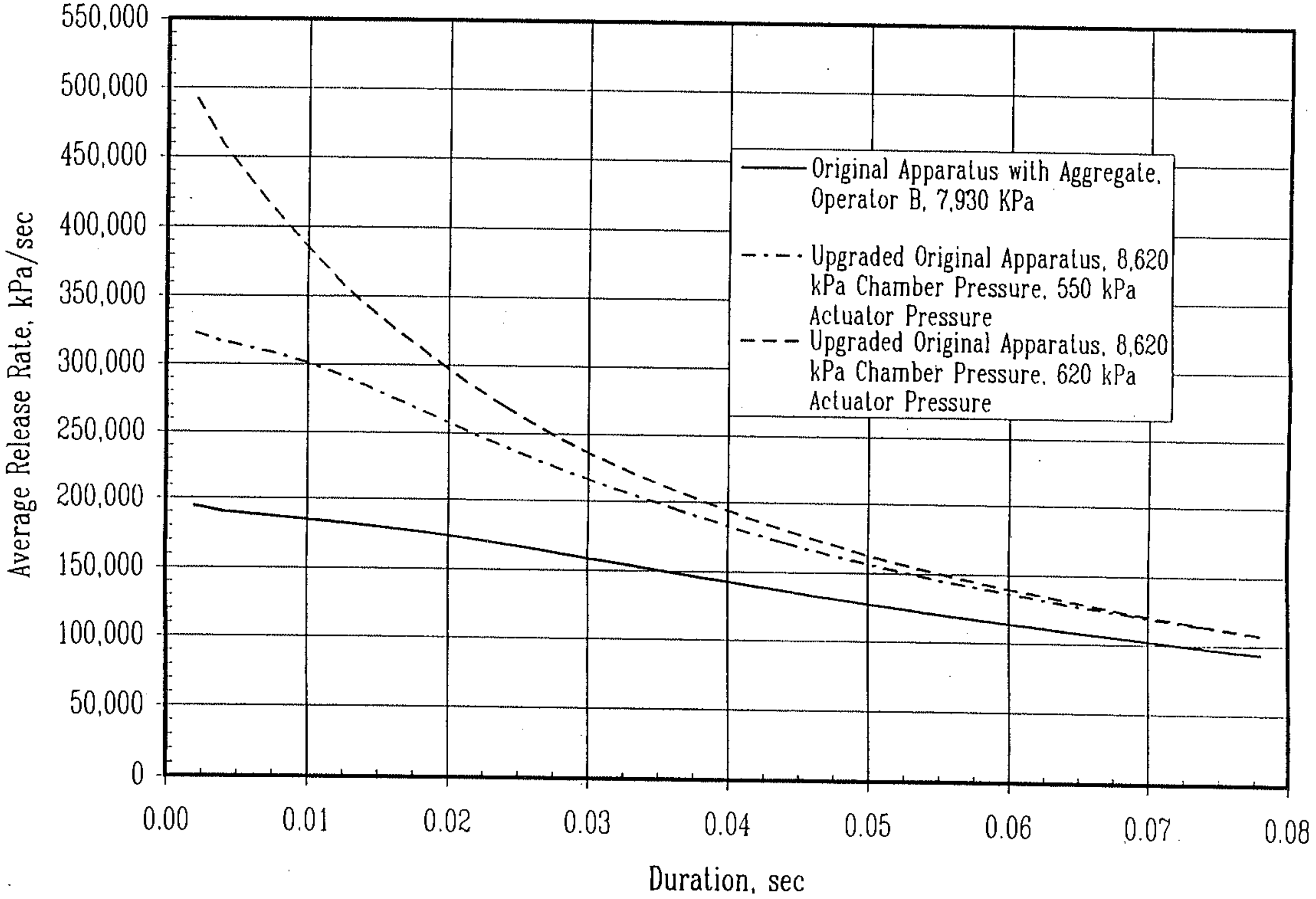


Figure B-12. Pressure Release Rates for the Original Apparatus with Aggregate and the Upgraded Original Apparatus without Aggregate at 8,620 kPa Initial Chamber Pressure

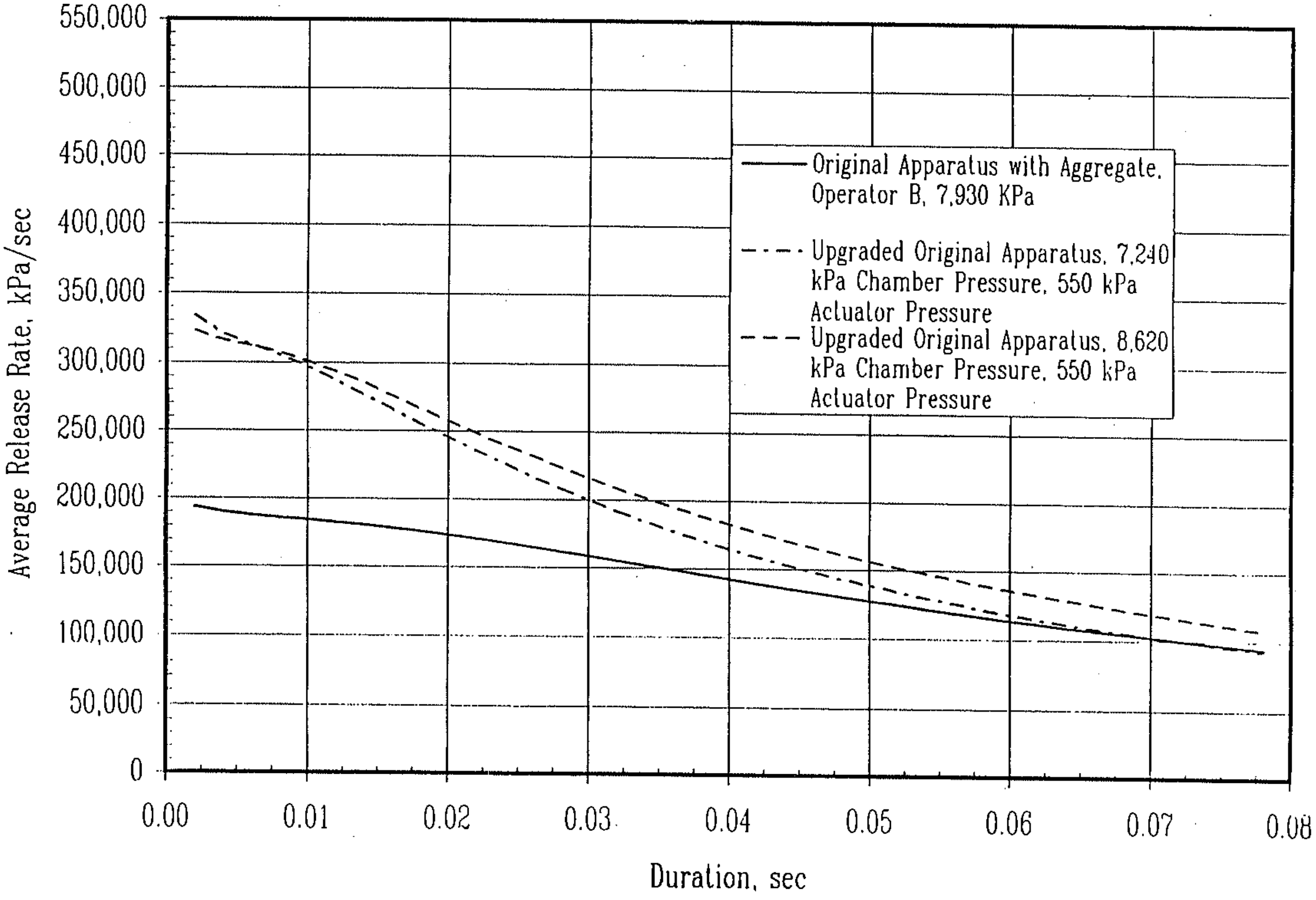


Figure B-13. Pressure Release Rates for the Original Apparatus with Aggregate and the Upgraded Original Apparatus without Aggregate at 7,240/550 and 8,620/550 kPa Initial Chamber Pressures

This suggests that short duration release rates are governed primarily by the actuator pressure, or how fast the valve is opened, and the duration for which a given release rate is maintained above is governed by the initial chamber pressure.

Figure B-14 shows the chamber configurations at which aggregate was tested, along with the Operator B original apparatus with aggregate pressure release rate curve for comparison. The researchers determined that aggregate should be tested at these initial conditions, 7,240/550 kPa, 7,930/590 kPa, and 8,260/620 kPa, because they produced a wide range of short duration release rates and initial pressures, which were, theoretically, primarily responsible for the WHFT fracture mechanism. It would have been interesting to test aggregate at 8,620/550 kPa as well, as this would have given WHFT results for two conditions with similar short duration release rates but different initial pressures. Unfortunately, this was not practical because the lower actuator pressure, coupled with the higher chamber pressure, caused the ball-valve to stick frequently, thereby limiting the ability to achieve reproducible pressure releases.

Upgraded Original Apparatus with Aggregate Release Rate Results

After the aggregate testing had been completed, release rate curves were produced for each of the upgraded original apparatus configurations tested. The results of this effort can be seen in Figures B-15, B-16, and B-17. The release rate curves for the calibration runs are also shown on the figures for comparison. Also, 95 percent confidence intervals for each configuration were calculated and plotted to aid in indicating significant differences. Note that the calibration run release rate curves are the average of two or three days of release rate testing (20 or 30 pressure releases), whereas the release rate curves with aggregate are the average of ten or more days of release rate testing (100+ pressure releases).

Figure B-15 shows the pressure release rate results for the upgraded original apparatus tested with aggregate at 7,240/550 kPa. The figure shows that the release rate

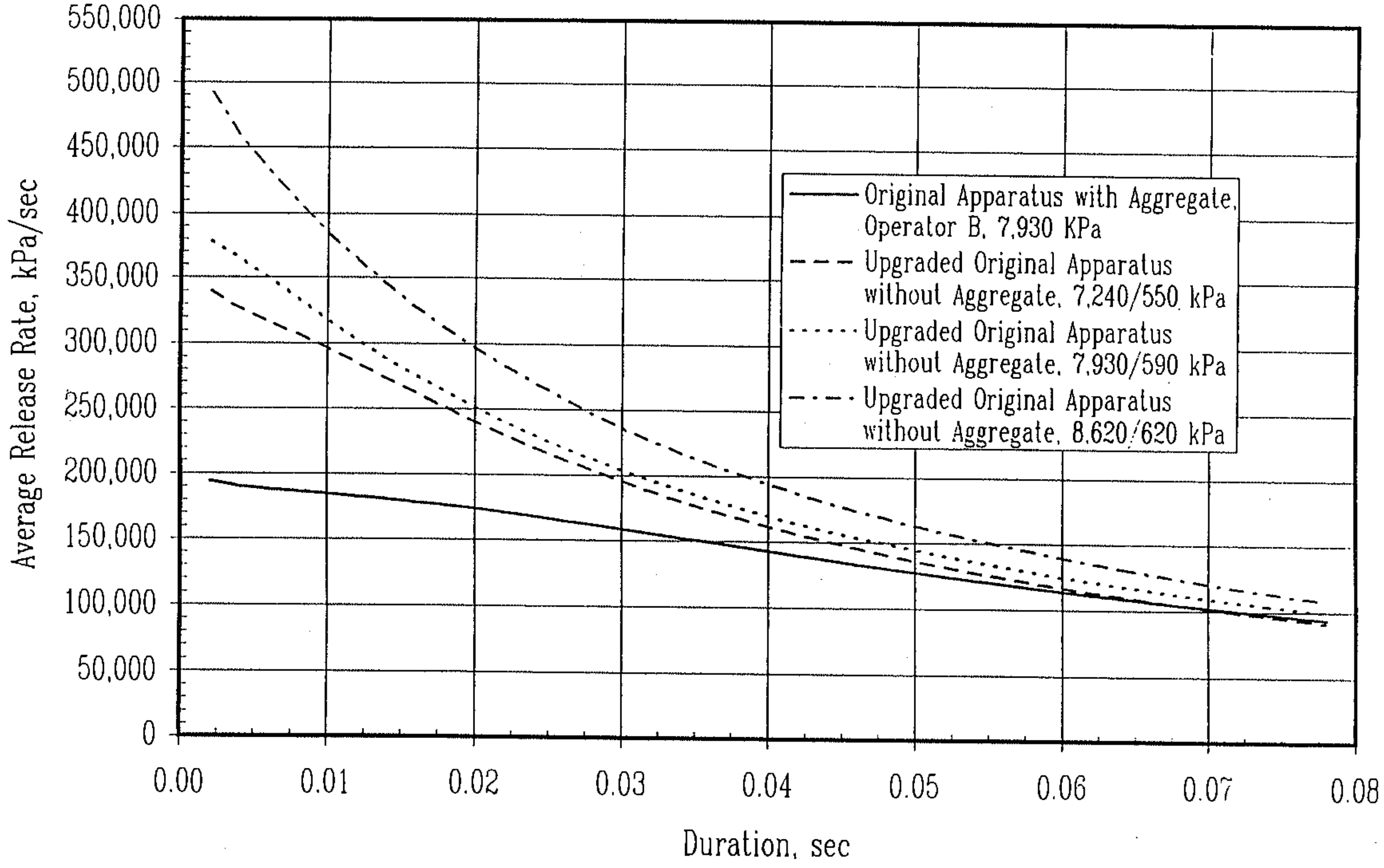


Figure B-14. Pressure Release Rates for the Original Apparatus with Aggregate and the Upgraded Original Apparatus at Various Pressure Configurations, without Aggregate

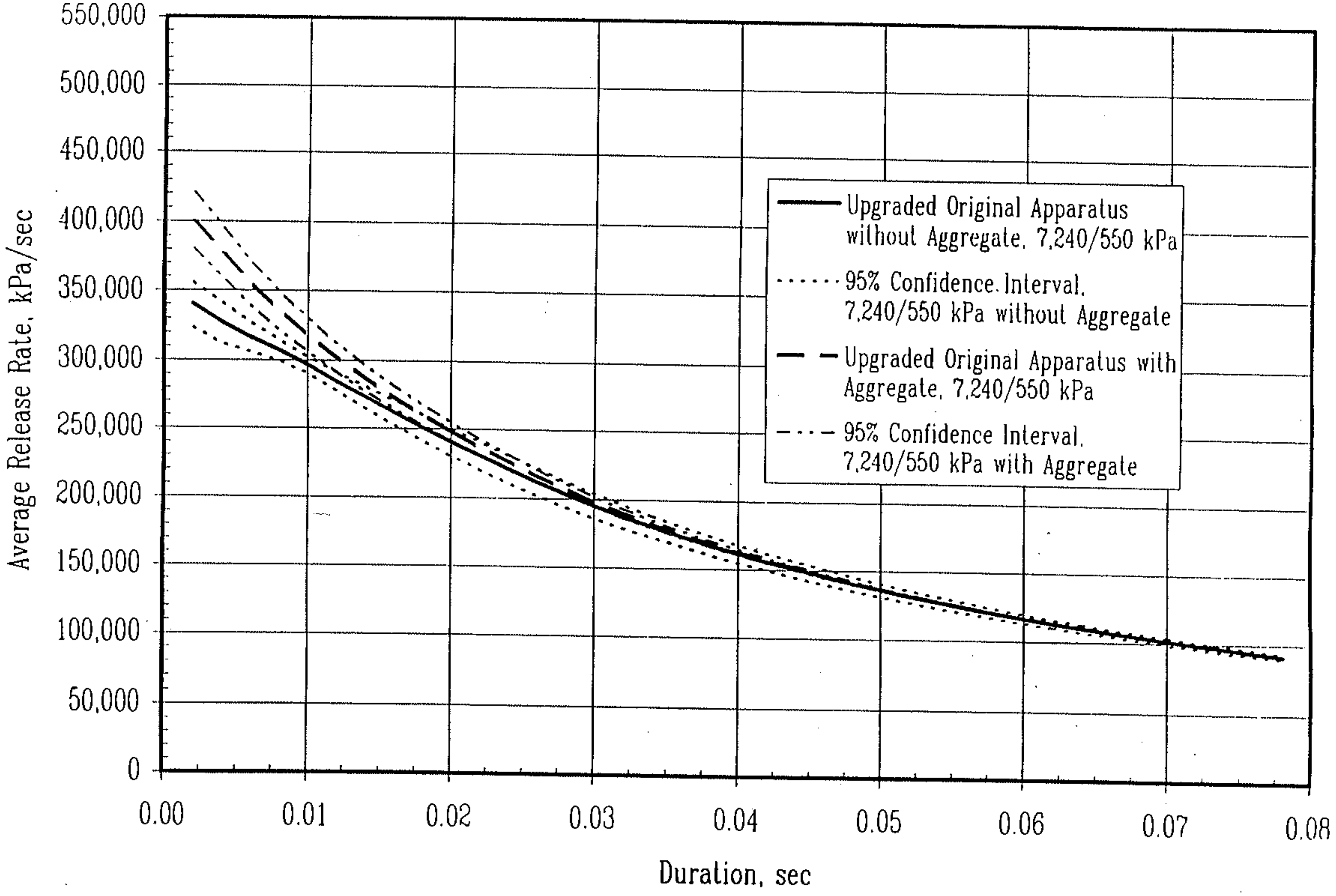


Figure B-15. Pressure Release Rates and 95 Percent Confidence Intervals for the Upgraded Original Apparatus at 7,240/550 kPa, With and Without Aggregate

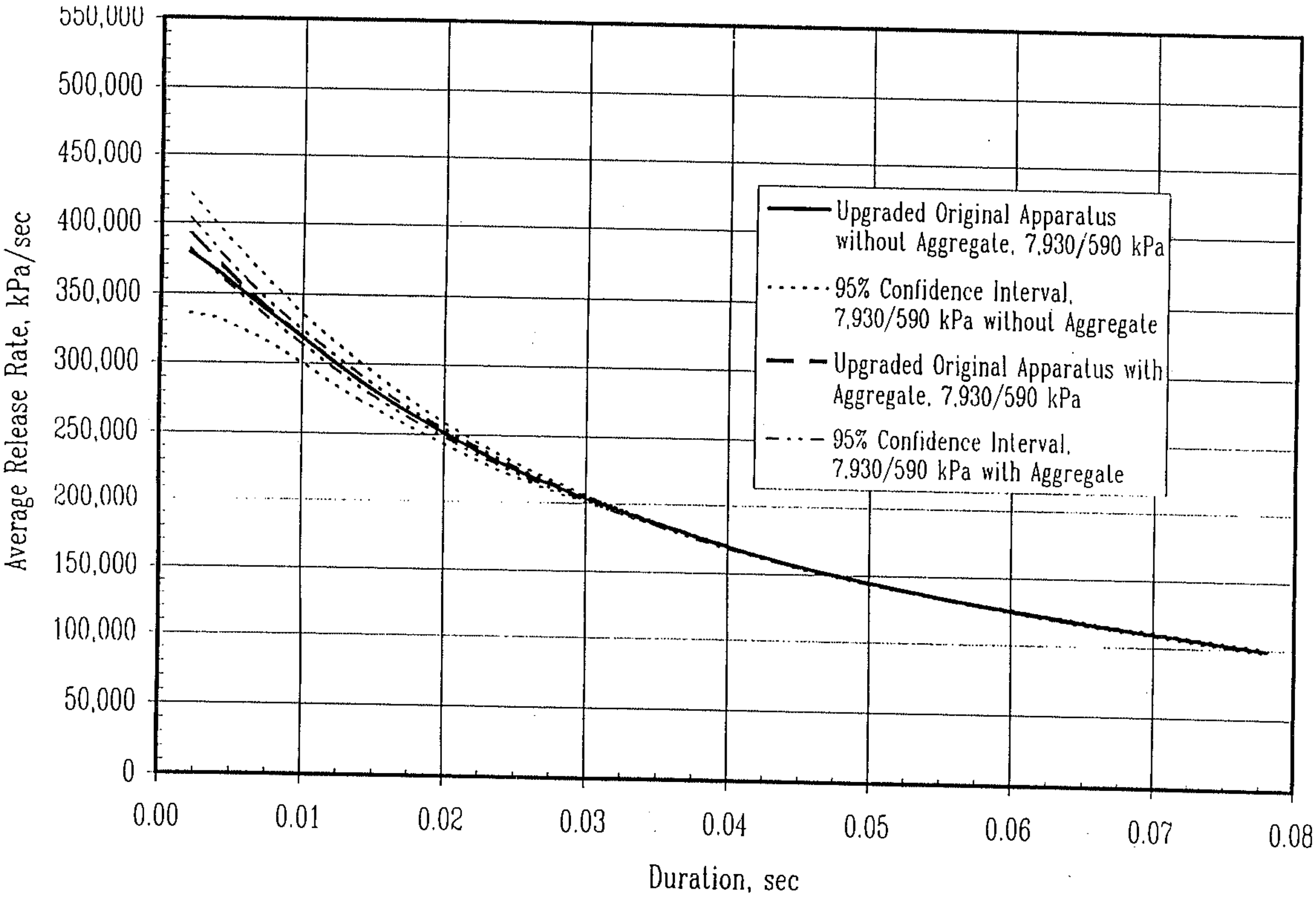


Figure B-16. Pressure Release Rates and 95 Percent Confidence Intervals for the Upgraded Original Apparatus at 7,930/590 kPa, With and Without Aggregate

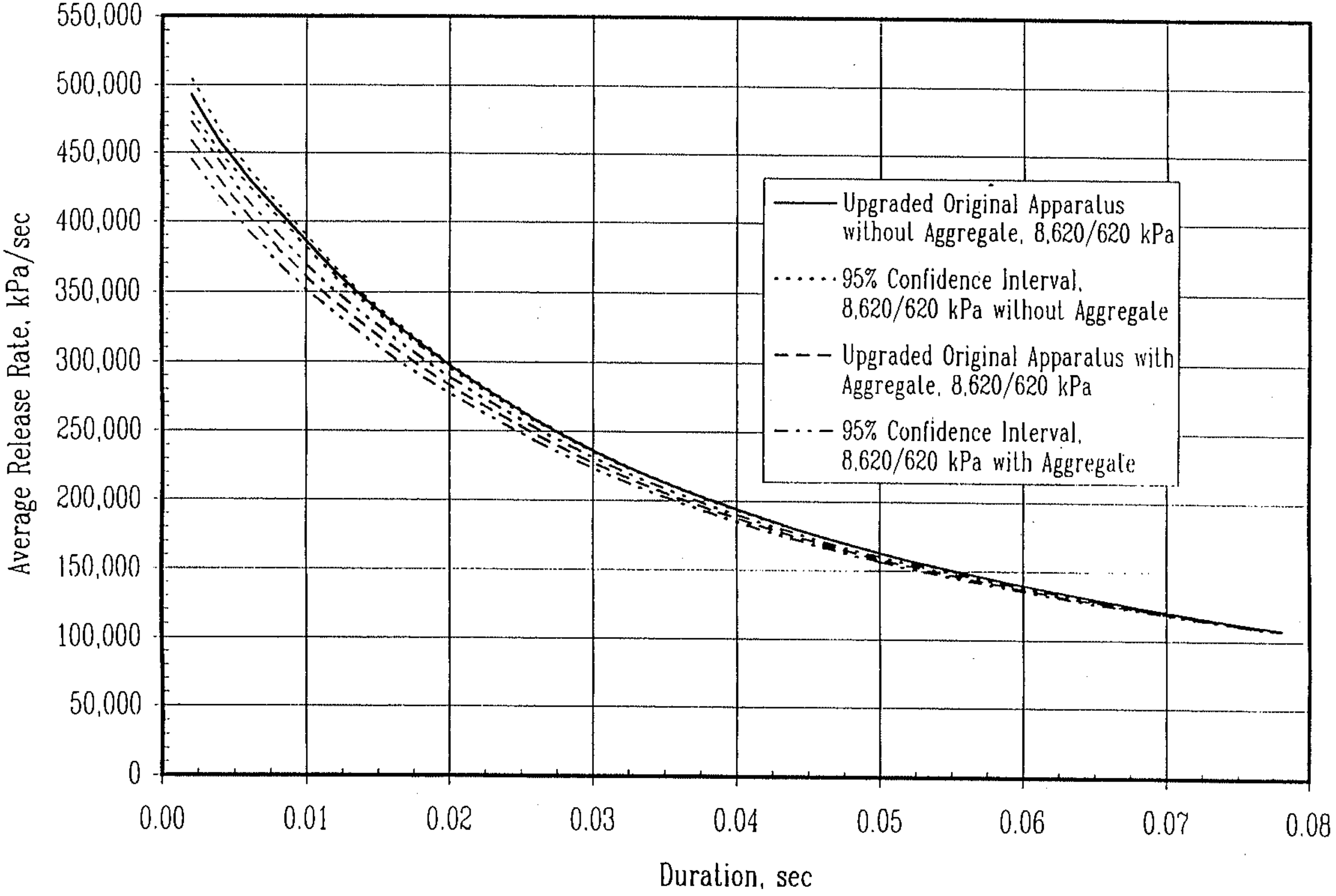


Figure B-17. Pressure Release Rates and 95 Percent Confidence Intervals for the Upgraded Original Apparatus at 8,620/620 kPa, With and Without Aggregate

with aggregate was higher for durations of less than approximately 0.035 seconds and was approximately 10 to 20 percent higher at very short durations. The difference may be due to the fact that the calibration test for this configuration was tested when the valve was fairly new. As a result, the valve had more resistance to turning. After repeated use, such as in aggregate testing, the valve may have turned more easily, thereby producing a faster release rate.

Figure B-16 shows the pressure release rate results for the upgraded original apparatus tested with aggregate at 7,930/590 kPa. The average release rates for the apparatus with and without aggregate conditions were much closer for this initial condition than for the 7,240/550 initial condition. However, a significant amount of variability appeared for the tests performed without aggregate. This can be partly attributed to the small number of calibration runs conducted. Also, during both calibration of the apparatus and aggregate testing, the valve had a tendency to resist turning. This may also have contributed to some of the variability shown.

Figure B 17 shows the release rate results for the upgraded original apparatus at 8,620/620 kPa. The curves show that the release rate for the condition without aggregate was consistently higher. The difference between the two curves ranges from approximately 5 to 10 percent at short durations. The curves also show that the variability for these two curves is somewhat smaller than that for the two previous configurations analyzed. Note that very little valve sticking was experienced at the 8,620/620 kPa configuration.

For comparison, Figure B-18 shows the average release rates with aggregate for the original apparatus and all configurations of the upgraded original apparatus. These curves were generated from the data collected during the WHFT testing, which will be discussed later. The figure shows that the release rates for the upgraded original apparatus at 7,240/550 and 7,930/590 were nearly identical.

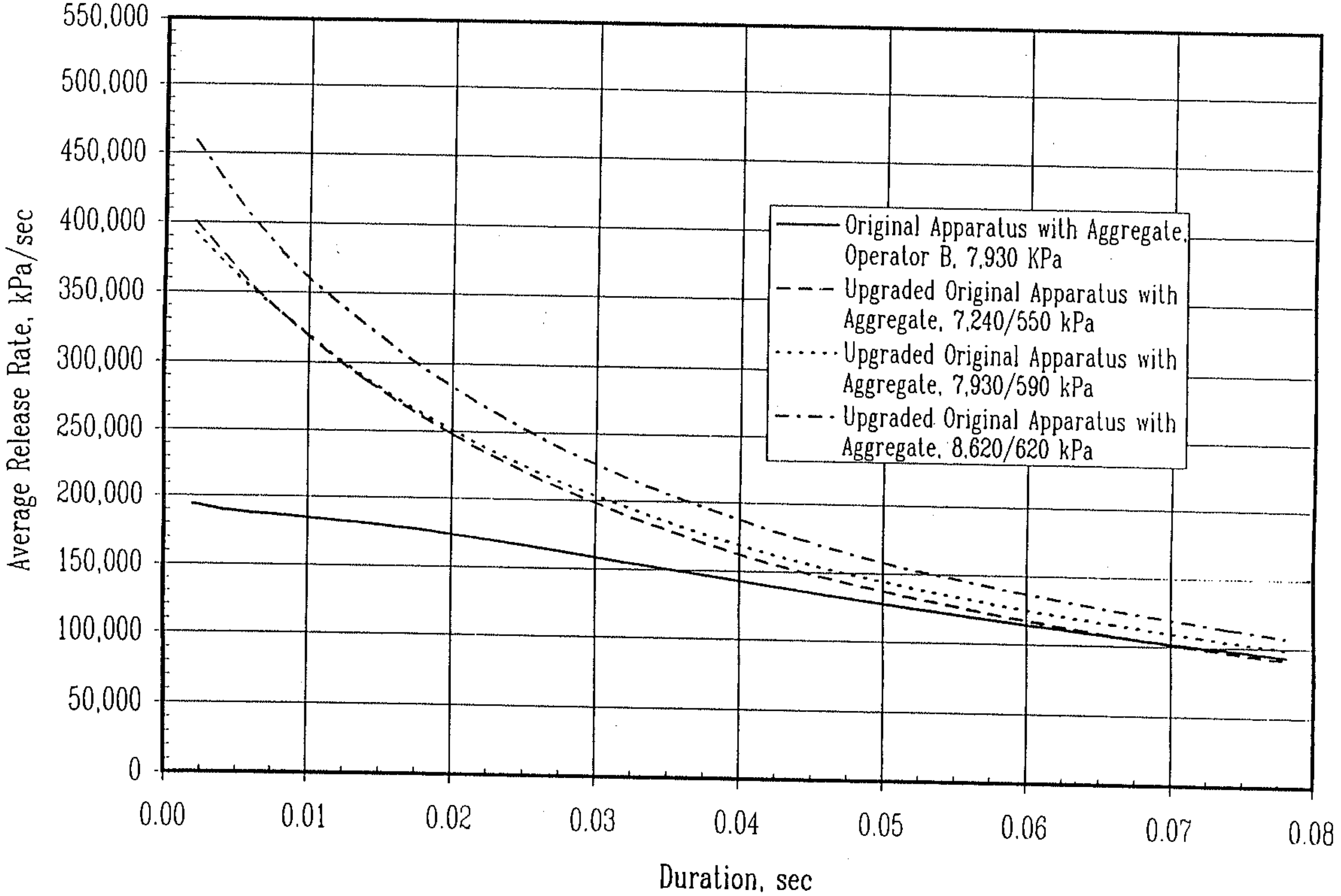


Figure B-18. Pressure Release Rates for the Original Apparatus with Aggregate and the Upgraded Original Apparatus with Aggregate

In general, increasing the actuator pressure appears to decrease the variability in the release rate curves. This makes sense, as a higher actuator pressure provides a greater force with which to turn the valve. Furthermore, researchers noted during the testing that an increase in the chamber pressure required an increase in the actuator pressure. This was due to the fact that an increase in the chamber pressure provided greater confining stresses on the ball valve, which, in turn, then required a greater force to open the valve.

6 Release Rate Variability

As indicated earlier in this work there was some concern regarding the magnitude of release rate variability, particularly with the original apparatus configuration. This concern led to the adoption of the upgraded original apparatus with the actuator. Two cases were analyzed: 1) the release rate variability for a single day, and 2) the release rate variability for consecutive days. To quantify the release rate variability, the coefficient of variation was calculated. The coefficient of variation is defined as

$$COV = (\sigma/\mu)\times 100 \quad \text{(Eq. B-7)}$$

where: COV is theCoefficient of Variation
σ is the Standard Deviation
μ is the average of a single run (10 releases)

The coefficient of variation changes for a given mean and standard deviation. Given that the mean and standard deviation are functions of the duration over which they are calculated, the variability factor can also be calculated for various durations.

The coefficient of variation is convenient for analyzing variability, as it normalizes the results on the basis of the average release rate. Obviously, an average release rate of 100,000 kPa/sec with a standard deviation of ± 20,000 kPa/sec is much more variable than an average release rate of 200,000 kPa/sec with a standard deviation of ± 20,000 kPa/sec.

Also, if less than ten consecutive pressure releases were to be analyzed, the coefficient of variation would increase because of increasing standard deviation with a smaller sample size, thereby reflecting the uncertainty due to the small sample size.

6.1 Single Day Release Rate Variability

On any single day of testing some variability in pressure release rate will occur. A typical day's testing is represented in Figure B-19. This figure shows the variation in pressure release rate for a typical WHFT run in the original chamber at a 7,930-kPa initial chamber pressure. The figure shows that the release rate can vary by as much as 15 percent at very short durations.

As noted earlier, one of the primary reasons for upgrading the original apparatus was to decrease this variability. To determine whether the variability had been decreased, the coefficient of variation was calculated for each of 10 days of WHFT testing in the original apparatus by Operator B (7,930 kPa), and these were then averaged. This average was then plotted against duration. The coefficient of variation was then calculated for each of at least 10 days of WHFT testing in the upgraded original apparatus at 7,240/550 kPa, 7,930/590 kPa, and 8,620/620 kPa, and then these were averaged. These averages were also plotted against duration. The results can be seen in Figure B-20.

In Figure B-20, the coefficient of variation curves for the upgraded original apparatus configurations for all durations is lower than the coefficient of variation curves for the original apparatus. This indicates that the upgraded original apparatus was less variable than the original apparatus. All of the curves show that the variability decreased with longer durations. This is consistent with the data shown in Figure B-19. It is also apparent from the curves in Figure B-20 that the variability of the upgraded original apparatus decreased at a faster rate than that of the original apparatus. The curves for the

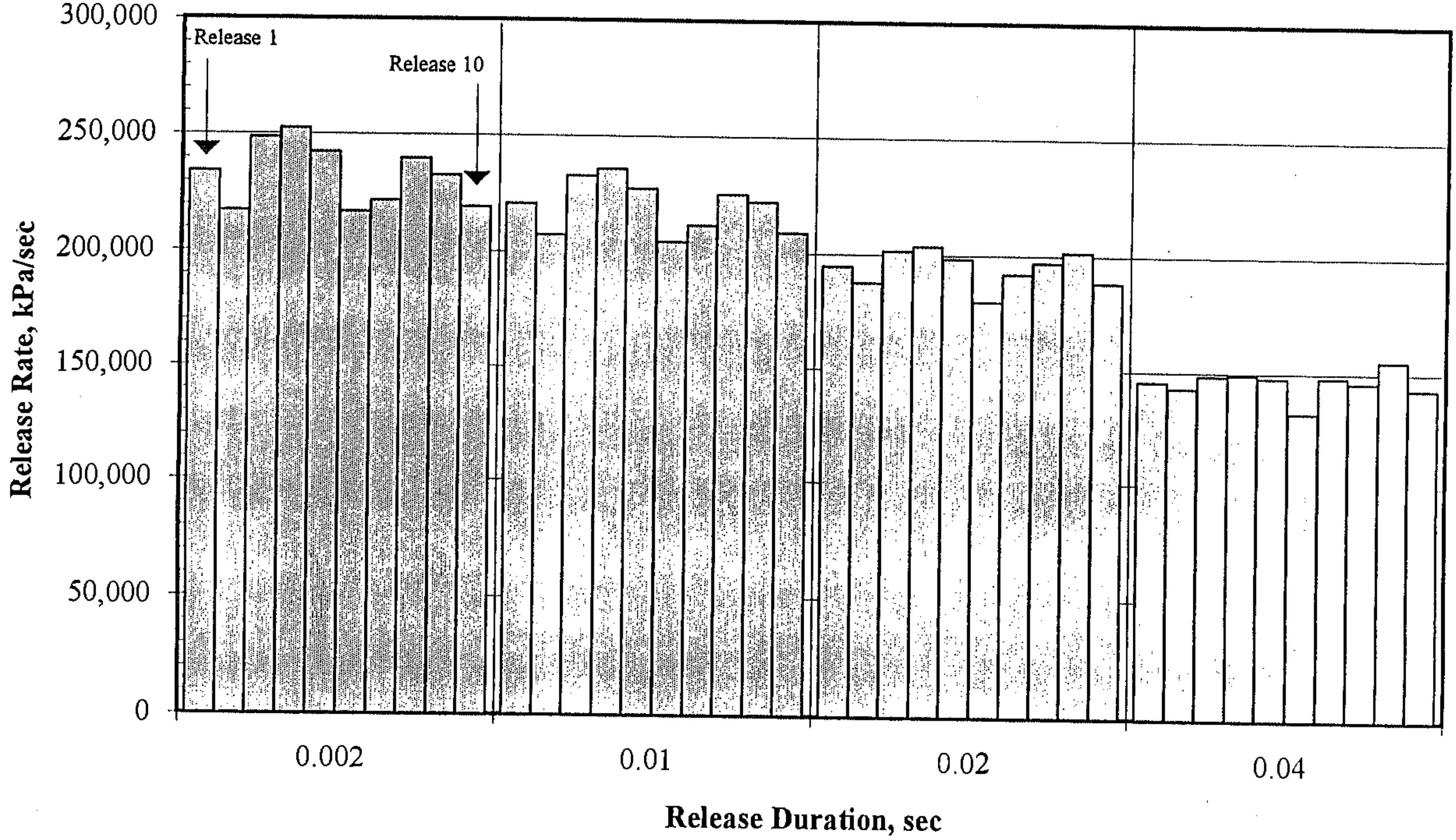


Figure B-19. Typical Individual Pressure Release Rates for Original Apparatus at 7,930 kPa Chamber Pressure

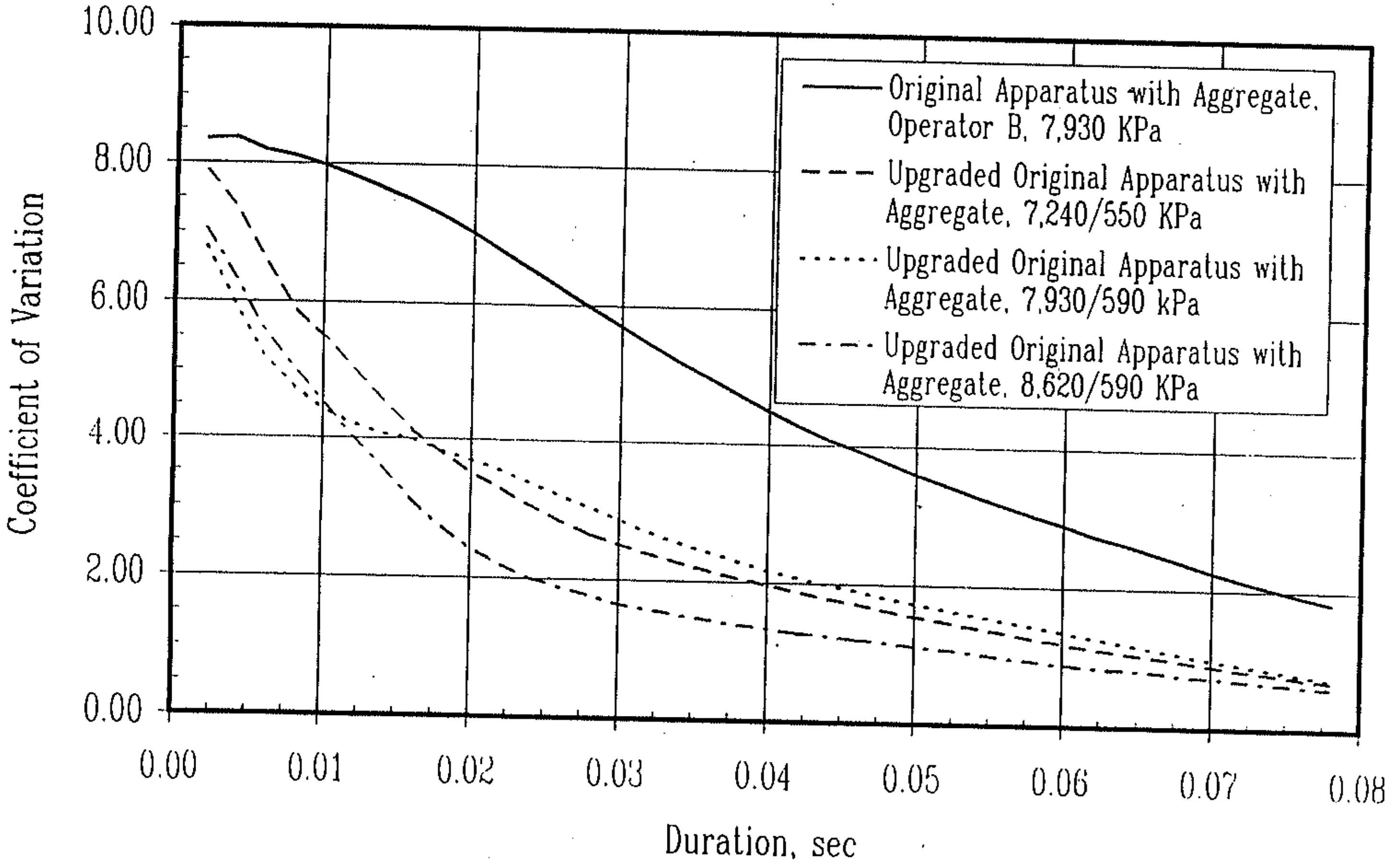


Figure B-20. Coefficient of Variation versus Duration for Original Apparatus with Aggregate and Upgraded Original Apparatus with Aggregate upgraded original apparatus also show a trend of decreased variability with increased actuator pressure. This is consistent with the information shown in Figures B-15, B-16, and B-17.

6.2 Day to Day Release Rate Variability

The day to day release rate variability was analyzed by determining how much the average daily release rate changed from day to day. This was calculated by plotting the average pressure release rate for the two scenarios (the average of ten days of WHFT testing) and then calculating their 95 percent confidence intervals. The results of this procedure can be seen in Figures B-21, B-22, and B-23. The bands corresponding to the upper and lower bounds of the release rates were plotted by taking the mean and adding or subtracting the calculated 95 percent confidence intervals. As Figure B-22 shows, the band width for the original apparatus is smaller (approximately 25,000 kPa/sec. at a 0.01-second duration) than that for the upgraded original apparatus at 7,930/590 kPa (approximately 30,000 kPa/sec. at a 0.01 second duration). This result is not particularly surprising, given that the pressure release valve tended to resist opening at this initial condition. The band widths for the 95 percent confidence intervals for the two other upgraded original apparatus configurations, 7,240/550 kPa and 8,620/620 kPa, are smaller than the 95 percent confidence interval band width for the original apparatus at 7,930 kPa, as tested by Operator B.

These results led to the conclusion that variability was decreased by upgrading the original apparatus. In addition to decreasing the variability, upgrading the apparatus increased its durability (valve maintenance was substantially reduced) and provided much greater control over the release rate (because of the electro-pneumatic actuator).

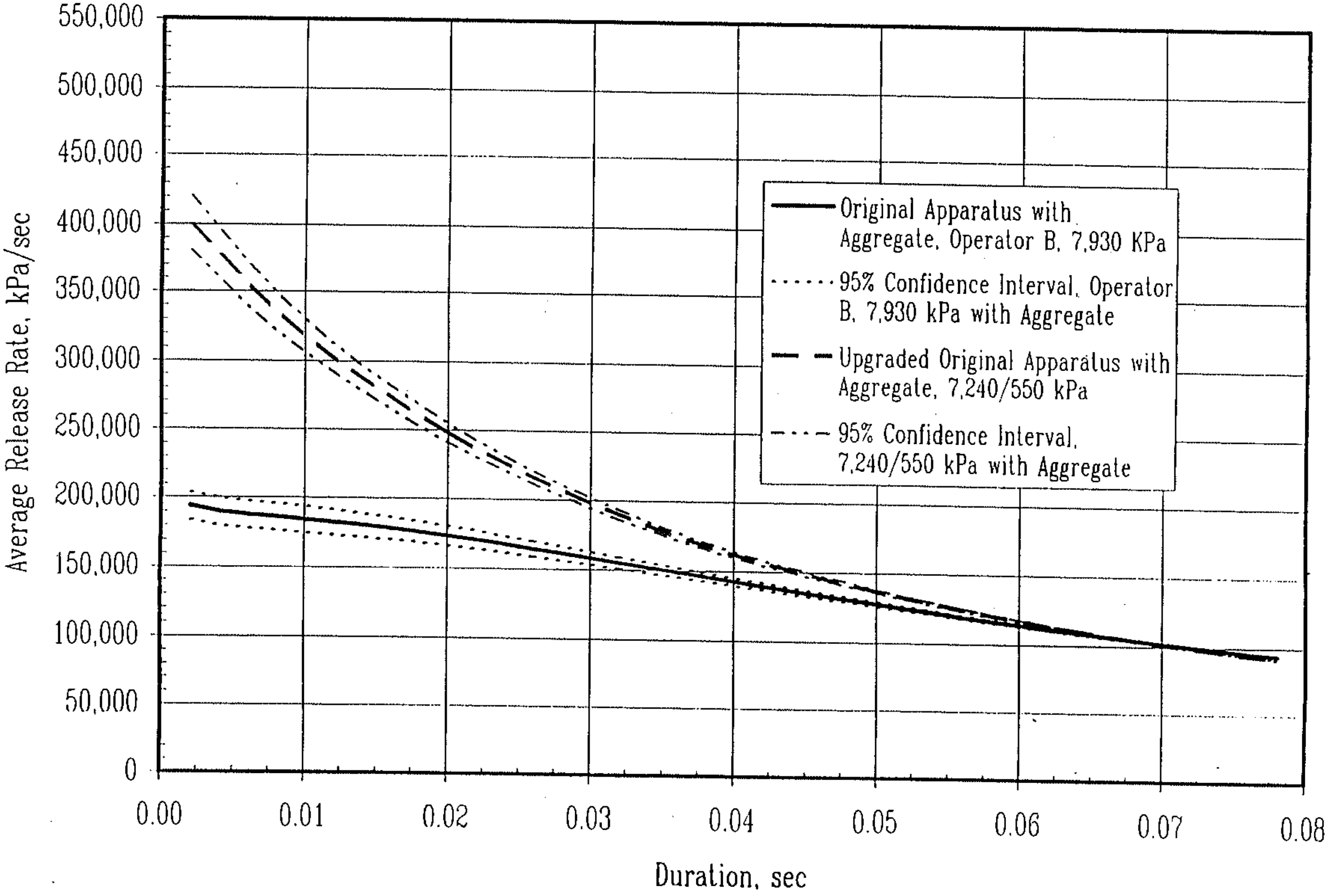


Figure B-21. Pressure Release Rates and 95 Percent Confidence Intervals for the Original Apparatus with Aggregate and the Upgraded Original Apparatus with Aggregate at 7,240/550 kPa

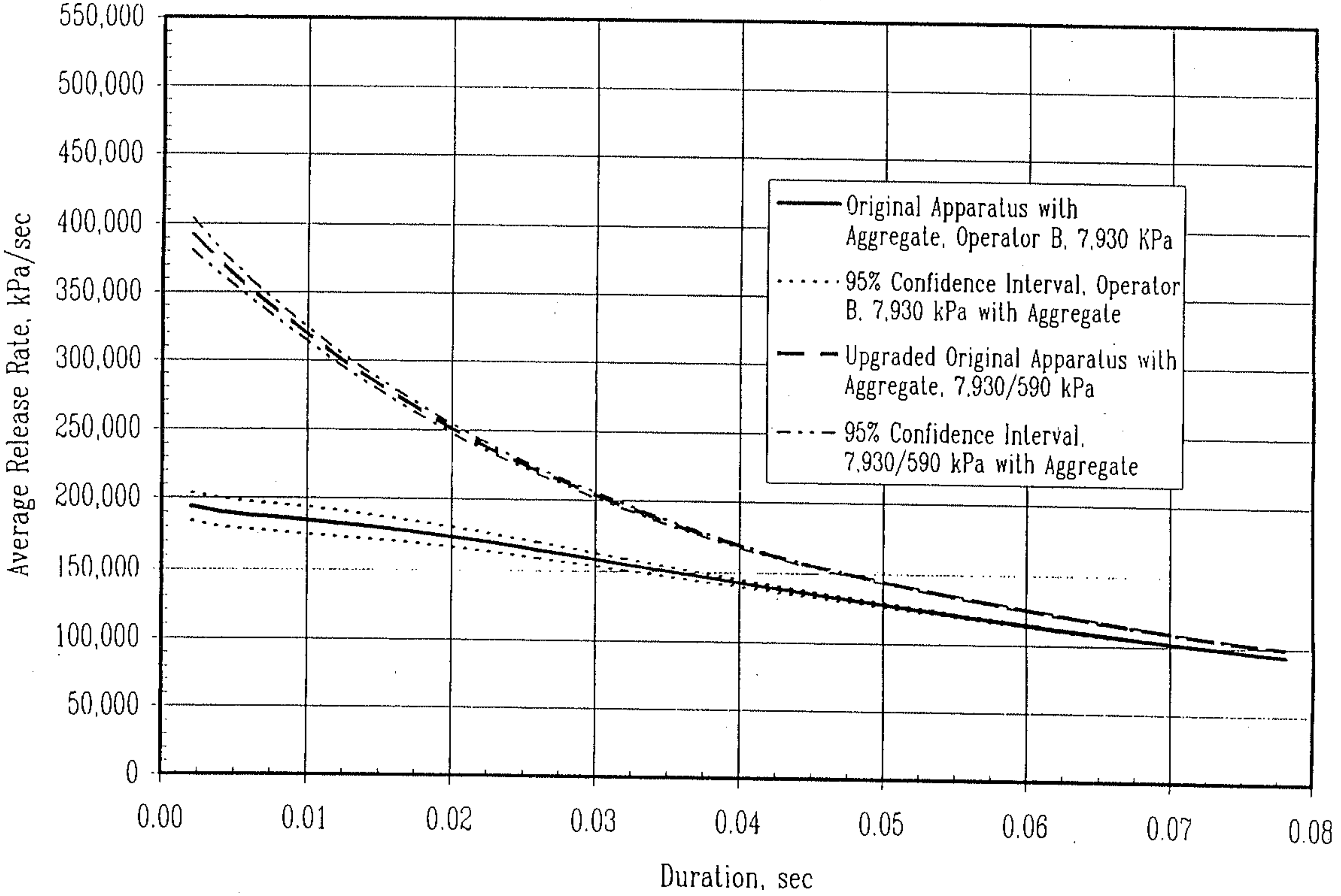


Figure B-22. Pressure Release Rates and 95 Percent Confidence Intervals for the Original Apparatus with Aggregate and the Upgraded Original Apparatus with Aggregate at 7,930/590 kPa

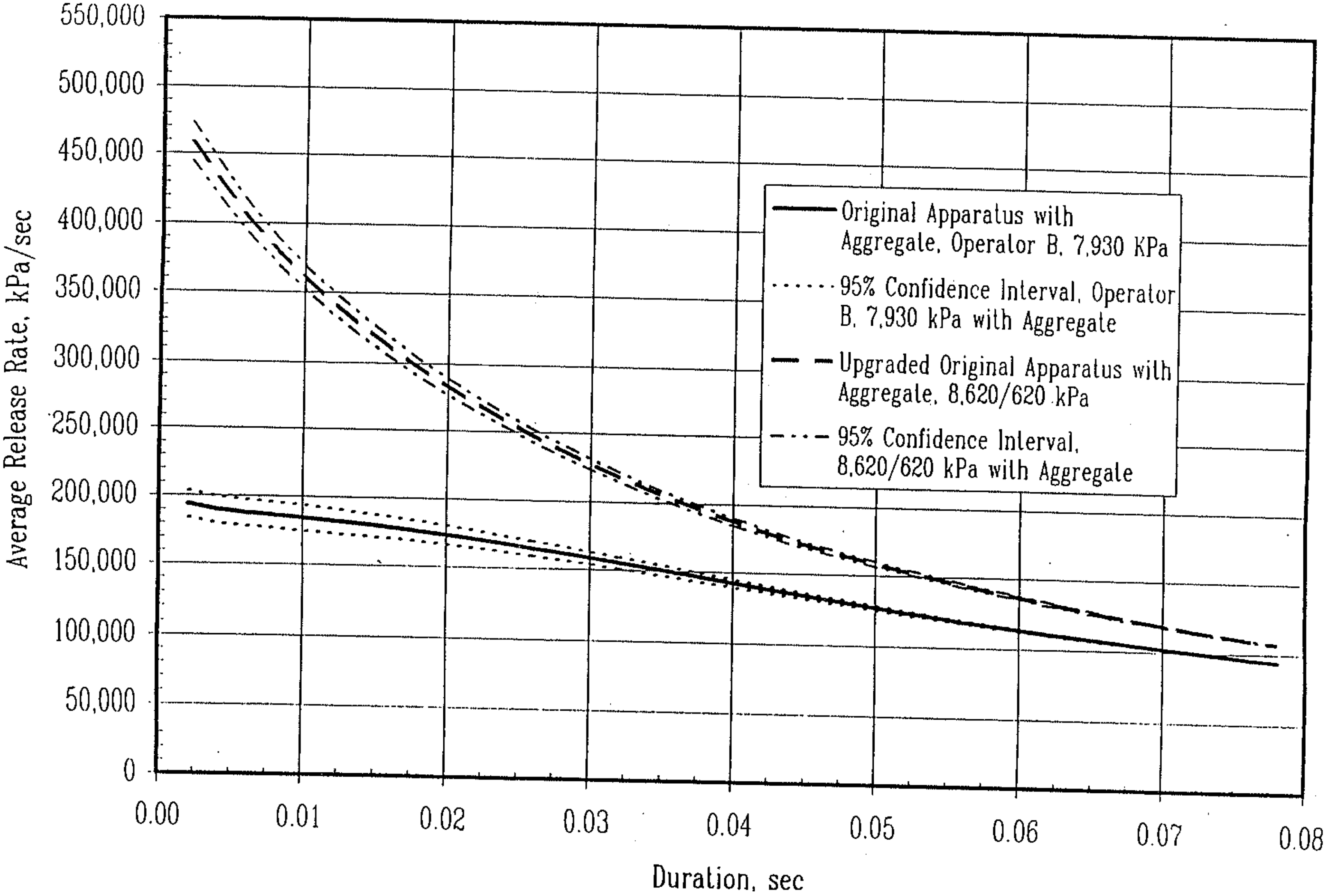


Figure B-23. Pressure Release Rates and 95 Percent Confidence Intervals for the Original Apparatus with Aggregate and the Upgraded Original Apparatus with Aggregate at 8,620/620 kPa

7 WHFT Results

7.1 Modified Large Apparatus Results

WHFT results for the modified large apparatus at initial chamber pressures of 7,930 kPa and 8,270 kPa are presented as percent fracture versus number of cycles in Figure B-24. Also shown in this figure, for comparison, are the WHFT results for the original apparatus at 7,930 kPa and the large apparatus at 8,270 kPa. Fracturing produced in the modified large apparatus at 8,270 kPa was higher than that produced in the original apparatus and in the large apparatus at 8,270 kPa.

7.2 Upgraded Original Apparatus

WHFT results for the upgraded original apparatus at initial conditions of 7,240/550 kPa, 7,930/590 kPa, and 8,620/620 kPa are presented as percent fracture versus number of cycles in Figure B-25. The upgraded original apparatus at initial conditions of 7,240/550 kPa produced less fracturing than the original apparatus. The upgraded original apparatus at initial conditions of 7,930/590 kPa produced more fracturing than the original apparatus, and the upgraded original apparatus at 8,620/620 kPa produced almost the same amount of fracturing as the original apparatus.

8 Analysis

A comparison of the percent fractures shown in Figures B-24 and B-25 with the release rates shown in Figures B-9 and B-18 suggests that there is no clear trend between short duration release rate and percent fracture. Furthermore, comparing initial chamber pressure to percent fracture does not show a clear trend, either. The release rates at 0.01 sec. duration and initial chamber pressures are summarized for the various WHFT apparatus configurations and initial pressures in Table B-3. The percent fractures at 50 pressurization cycles, as well as the HFI, are also shown.

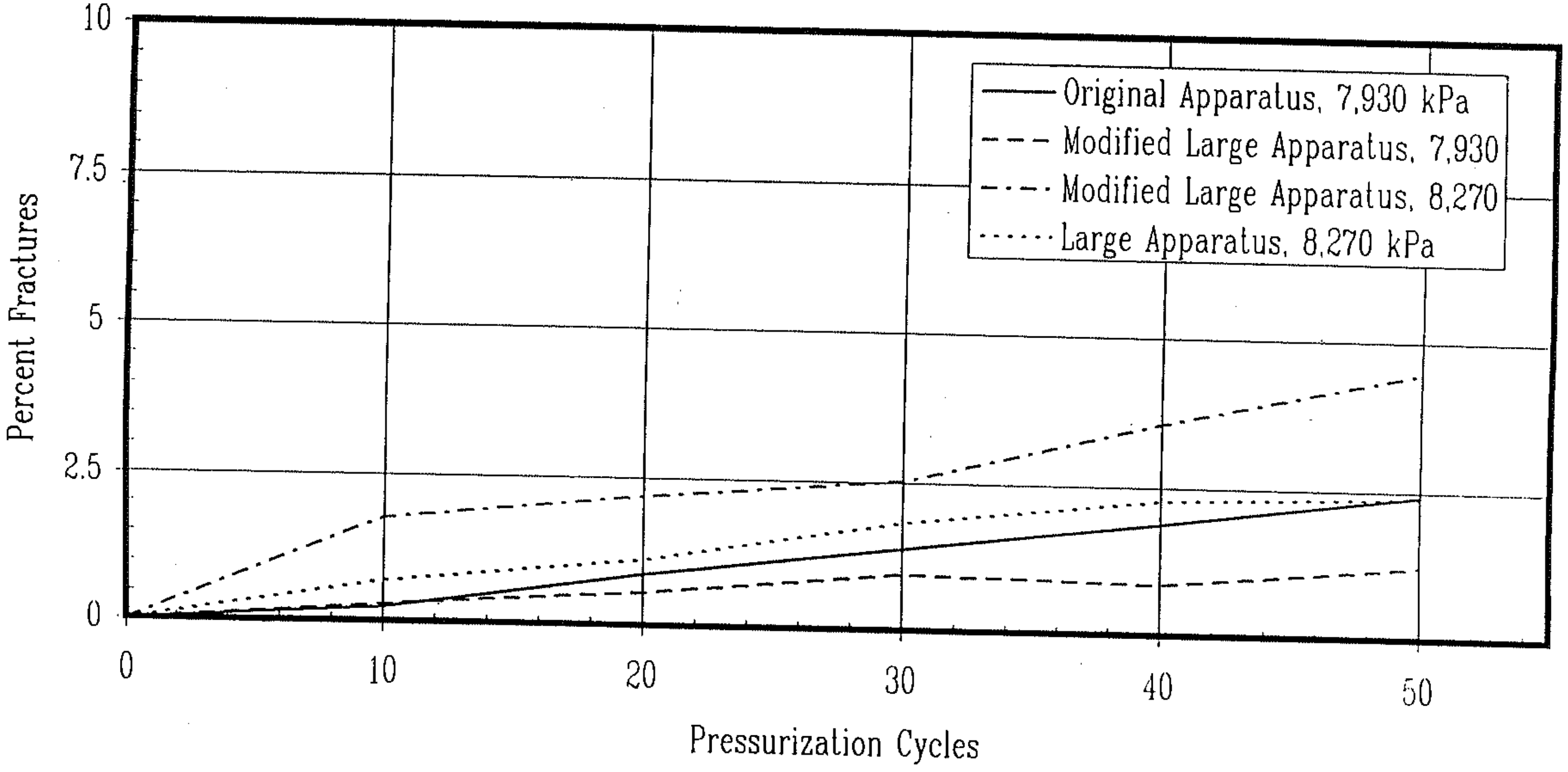


Figure B-24. Percent Fractures versus Number of Cycles for Original, Large, and Modified Large Apparatus

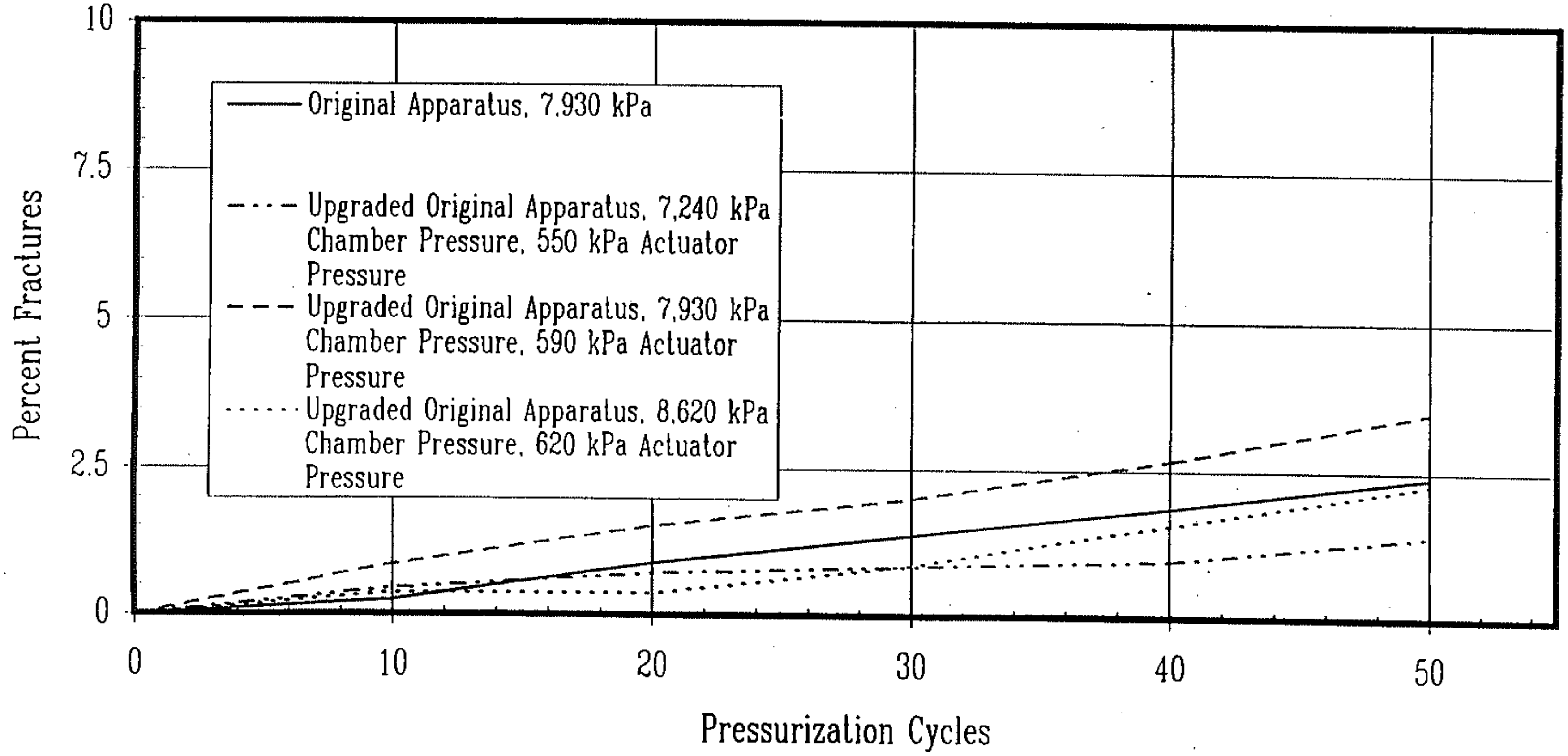


Figure B-25. Percent Fractures for Original and Upgraded Original Apparatus

Table B-3 Summary of Pressure Release Rates, Initial Chamber Pressures, and Fracture Percentages.

Apparatus Configuration	**Initial Pressure (kPa)**	**Release Rate at 0.01 sec. (kPa/sec.)**	**Percent Fractures After 50 Cycles**	**HFI**
Modified Large Apparatus	8,270	211,700	4.5	66
Upgraded Original Apparatus	7,930/590	319,100	3.5	71
Original Apparatus	**7,930**	**184,400**	**2.4**	**104**
Large Apparatus	8,270	183,300	2.4	104
Upgraded Original Apparatus	8,620/620	360,400	2.3	109
Upgraded Original Apparatus	7,240/550	318,300	1.4	180
Modified Large Apparatus	7,930	213,600	1.2	206

Table B-3 shows no clear relationship between either release rate, initial pressure or percent fracture. To determine whether the percent fracture is a function of release rate and initial chamber pressure, the average release rate shown in Table B-3 was plotted against the corresponding initial chamber pressure. The corresponding percent fracture was then written next to the plotted point. The result of this procedure can be seen in Figure B-26, which appears to show an area of greater fracturing. This area is represented on the graph by the hatch marks.

In general, it appears that increasing the release rate has a positive effect on the percent fracture. Also, it appears that a chamber pressure in the range of 7,930 to 8,270 kPa is necessary to produce substantial fracturing. Release rates below approximately 210,000 kPa/second and pressures outside of the 7,930 to 8,270 kPa range produced very little fracturing. It is possible that low initial apparatus pressures did not produce substantial fracturing because water was not forced deep enough into the aggregate pores.

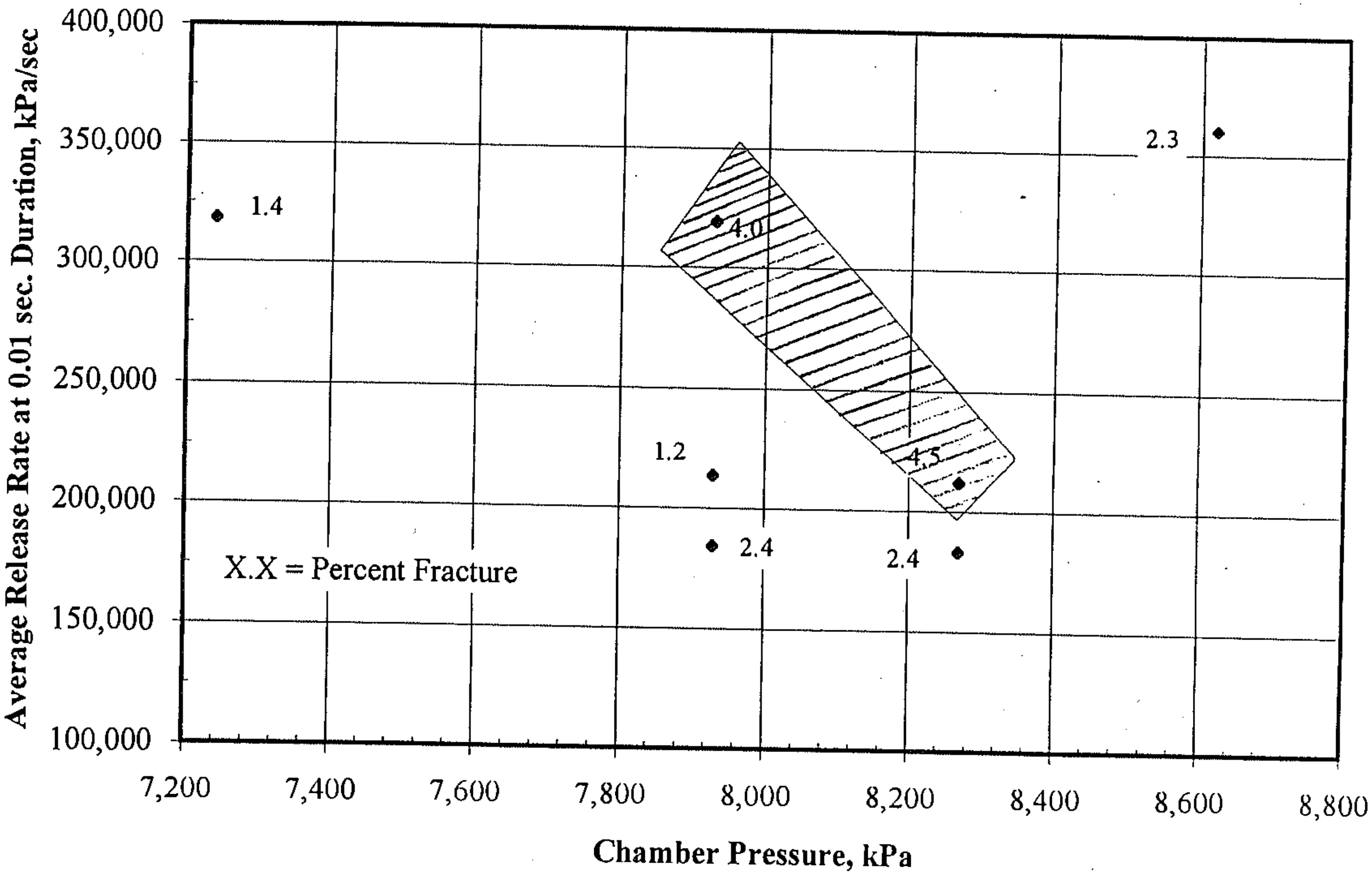


Figure B-26. Average Release Rate versus Chamber Pressure

The length of flow path provided to produce internal hydraulic pressure is directly related to the initial chamber pressure. If the flow path is not long enough, relative internal pressures greater than the tensile strength of the aggregate will not be developed when compressed air expands in the pore because of the chamber pressure release. High initial pressures may limit fracturing by causing too much air to be dissolved into the water. As stated earlier, water is able to hold more air in solution at higher absolute pressures. Therefore, the higher the initial chamber pressure, the easier it is for the aggregate to become saturated. If, by the time pressure is released, very little compressed gaseous air is left to expand, the aggregate will not hydraulically fracture.

No apparatus configuration in this study produced an excessive amount of fracturing (i.e., 20 percent to 30 percent), even though the short duration release rates ranged from 180,000 kPa/sec. to 360,000 kPa/sec. This result does not necessarily mean that there is no upper bound release rate that will cause non-D-cracking susceptible aggregates to fracture. It simply indicates that an upper bound release rate was not achieved in this study.

9 Conclusions

The testing performed as a part of this research investigated various apparatus configurations performing the WHFT procedure in an attempt to determine how to calibrate the equipment to produce consistent results. The WHFT procedure was shown to be somewhat sensitive to the magnitude of pressure release rates at short durations, and a minimum rate of 210,000 kPa at a duration of 0.01 sec. was proved necessary to produce significant fracturing. No upper bound pressure release rate that caused excessive fracturing was identified, although one may exist. There also seemed to be a relationship between high actuator pressures and low release rate variability for the upgraded original apparatus, as the higher actuator pressures prevented the pressure release valve from sticking. Given this, and the evidence that higher release rates used in this study did not skew the WHFT results, the researchers recommend that the actuator pressure be kept high enough to limit the release rate variability. On each specific piece of equipment, calibration tests will have to be run to determine the actuator pressure that will prevent another pressure release valve from sticking closed.

The specified initial pressure of 7,930 kPa for the original WHFT apparatus falls into the range of initial pressures that produced substantial fracturing for this aggregate. In general, it appears that low initial pressures will not produce substantial fracturing, as water is not forced deep enough into the aggregate pores. On the other hand, high initial pressure also may not produce substantial fracturing, as the aggregate sample may become almost fully saturated. A maximum release rate and associated duration, as well as initial pressure, that would avoid excessive fracturing were not determined.

10 References

1. Almond, D.K., "A Test for Identifying Aggregates Susceptible to Freeze-Thaw Damage," Masters Thesis, Department of Civil Engineering, University of Washington, June 1990.

2. Janssen, D.J., and Snyder, M.B., "Resistance of Concrete to Freezing and Thawing," SHRP-C-391, *Transportation Research Board*, June 1994.

3. Timoshenko, Stephen, "Theory of Plates and Shells," McGraw-Hill, New York, 1987.

Appendix C

Proposed MTM xxx Test Procedure

MTM XXX
Proposed Method of Test
for

Hydraulic Fracture of Coarse Aggregate

1. SCOPE

1.1 This test method covers the resistance of aggregates to fracture under the effect of internal pressure expelling water from aggregate pores. The procedure is intended to assist in the identification of aggregates that cause deterioration in concrete when exposed to repeated cycles of freezing and thawing (D-cracking).

1.2 This procedure may involve hazardous materials, operations, and equipment. This procedure does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this procedure to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

2.1 *AASHTO Standards*

T 2	Sampling Aggregates
M 92	Wire Cloth Sieves for Testing Purposes
M 231	Weights and Balances Used in The Testing of Highway Materials

2.2 *ASTM Standards*

C 702	Method for Reducing Field Samples of Aggregate to Testing Size
D 3665	Practice for Random Sampling of Construction Materials

2.3 *MTM Procedures*

MTM 115Rapid Freezing in Air and Thawing in Water

3. SIGNIFICANCE AND USE

3.1 As noted in the scope, the procedure described in this method is intended to aid in the identification of D-cracking susceptible aggregates. Aggregates that exhibit a high percentage of fracturing under repeated pressurization cycles are considered to be more likely to cause D-cracking in field applications.

3.2 The relative short time (approximately eight working days) required for completion of this procedure makes it appropriate for use as a screening test to identify questionable aggregates requiring additional (and more time consuming) testing (such as MTM 115) prior to approval.

3.3 This method is sensitive to the size of the aggregate pieces, and may be appropriate for identifying maximum aggregate size reductions necessary to avoid D-cracking.

3.4 This method is also sensitive to the number of non-durable particles in a sample, and may be appropriate for determining the percentage of durable aggregate that must be blended with non-durable aggregate in order to produce a blend with low enough D-cracking potential to provide acceptable performance.

4. APPARATUS

4.1 *Tumbling Apparatus:*

4.1.1 The tumbling apparatus (hereafter referred to as the tumbler) shall consist of a rubber drum for holding the sample and a motorized drive unit.

NOTE 1 - A suitable tumbler is available commercially as a rock tumbler for polishing rocks. Various sizes are available.

4.1.2 The rubber drum shall have inside dimensions of approximately 170 mm (6-3/4 in.) diameter by 200 mm (8 in.) deep. The inside shall be faceted to assist in the tumbling of the aggregate pieces. The drum shall have a removable cover to facilitate placing the sample in the drum, and the cover should not interfere with the rotation of the drum when in the motorized drive unit.

4.1.3 The motorized drive unit shall be capable of rotating the drum on its side at a rate of 30 (±5) revolutions per minute.

4.2 *Pressurization Apparatus:*

4.2.1 The pressurization apparatus shall consist of a pressure chamber able to safely withstand operating pressures of 10,000 kPa (1500 psi), a compressed Nitrogen source and adjustable pressure regulator with gauge having an output capacity of up to 10,000 kPa (1500 psi), appropriate valves and fittings to permit filling with water and draining along with pressurization/rapid pressure release, and a stand to permit a 135° rotation of the pressurization apparatus.

4.2.2 The inside of the chamber shall be suitable treated to prevent the physical fracture of aggregates by the expansion and contraction of the chamber from pressurization/pressure cycles.

NOTE 2 - For a cylindrical steel chamber with 25 mm-thick (1 in.) walls and having inside dimensions of 254 mm (10 in.) diameter by 51 mm (2 in.) high, a neoprene rubber sheet with a thickness of 0.8 mm (1/32 in.) glued to the inside ends of the chamber has proven sufficient. No treatment was necessary for the inside wall of the cylinder.

NOTE 3 - Shop-built pressure chambers are not recommended due to the difficulty with obtaining pressure-tight seals at the high pressures involved, as well as the hazards associated with high-pressures. If a shop-built pressure chamber is used, it should be pressure-certified to provide a safety factor of at least 5 to 1.

4.2.3 The pressure chamber shall be fitted with necessary valves and fittings to permit the application of pressure (pressure valve), release of pressure (pressure release valve), filling with water (fill valve), and draining (drain valve). Additional valves and fittings may be provided where appropriate by the equipment manufacturer in order to achieve the necessary pressure-release rate. (Section 4.2.5)

4.2.4 A pressure regulator and gauge that attaches directly to a compressed Nitrogen cylinder shall be provided. The regulator shall have a capacity of 10,000 kPa (1500 psi). The gauge shall have a precision of 0.25% of full scale.

4.2.5 The apparatus should be capable of producing a drop in pressure of at least 2,100 kPa (300 psi.) during a time interval of 0.01 second when the pressure release valve is opened. This drop in pressure is termed the pressure release rate for a time duration of 0.01 second. The procedure for measuring the pressure release rate is described in Appendix A.

4.3 *Drying Oven:*

The drying oven should allow free circulation of air through the oven and should be capable of maintaining a temperature of 110°C ±5°C (230°F ±9°F).

4.4 *Balance:*

The balance should conform to the requirements of AASHTO M 231 for the class of general purpose balance required for the principal sample mass of the sample being tested.

5. SPECIAL SOLUTIONS REQUIRED

5.1 A solution of alkylalkoxysilane in water (referred to as silane solution) is used in Step 7.3 as part of the sample preparation.

5.2 Appropriate precautions in handling the silane solution should be observed.

NOTE 4 - An appropriate silane solution is available commercially as Enviroseal 40 from Hydrozo, Inc.

NOTE 5 - Some aggregates absorb water at a very rapid rate which prevents them from fracturing in the following test procedure. The silane treatment described in Step 7.3 reduces the absorption rate by effectively making the aggregates more hydrophobic. This treatment has been demonstrated to have no effect on the hydraulic fracture performance of aggregates with slower absorption rates.

6. SAMPLES

6.1 Representative samples of aggregate sources should be obtained by appropriate means and in accordance with accepted procedures such as AASHTO T 2 and ASTM C 702 and D 3665.

6.2 Samples will be divided into individual size ranges (step 7.1 below). Appropriate size ranges may include passing the 32 mm (1 1/4 in.) but retained on the 19 mm (3/4 in.) sieves and passing the 19 mm (3/4 in.) but retained on the 12.5 mm (1/2 in.) sieves.

6.3 Duplicate specimens may be run to obtain acceptable variability, and sufficient material should be collected in the initial sample to provide the necessary number of particles in each desired size range. Preliminary work has indicated that 600-800 particles in a given size range is desirable.

7. PREPARATION OF TEST SAMPLE

7.1 Separate the sample into appropriate size ranges by sieving to refusal using approved wire screens (AASHTO M 92). Individual specimens should contain sufficient aggregate to fill the pressure chamber.

7.2 The aggregate specimens should be thoroughly washed and dried to a constant mass at a temperature of 110°C ±5°C (230°F ±9°F), and allowed to cool to room temperature.

NOTE 6 - Adequate ventilation should be supplied for the following three steps. The use of a fume hood may be appropriate.

7.3 Place the aggregate specimen in the silane solution making sure that all aggregate pieces are covered. Allow the specimen to remain in the silane solution for 30 (±5) seconds.

7.4 Remove the specimen from the silane solution and allow the excess solution to drain for five minutes.

NOTE 7 - Strainers suitable for immersing the aggregate in the silane solution and draining are readily obtainable from restaurant supply sources.

NOTE 8 - The silane solution may be re-used if it is placed in a sealed container between uses. The solution should be discarded if it begins to thicken.

7.5 Dry the specimen to a constant mass at a temperature of 110°C ±5°C (230°F ±9°F), and allow to cool at room temperature for one hour.

8. PROCEDURE

8.1 Place enough of the specimen into the tumbler to fill it approximately half way and tumble for 1 minute (±5 seconds). Separate out any pieces passing the 9.5 mm (3/8 in.) sieve. Repeat for the remainder of the specimen. Determine the mass to the nearest gram and count the number of pieces retained on the 9.5 mm (3/8 in.) sieve. Record these numbers as the initial mass and number of particles, m_0 and n_0, respectively.

8.2 Place the specimen into the pressure chamber, and close the chamber as directed in the manufacturer's instructions. Rotate the apparatus from the filling (horizontal) to the testing (vertical) position.

8.3 Close the pressure valve and open the main valve on the Nitrogen tank. The pressure regulator should be set to the pressure indicated on the calibration sheet provided with the equipment.

NOTE 9 - At this time a minimum pressure of 7,930 kPa (1150 psi.)should be used. Further work may justify a lower pressure, but at present this should be the minimum pressure used.

8.4 Fill the pressure chamber with water in accordance with the manufacturers instructions. Remove air bubbles from the chamber by pivoting the chamber approximately 45° either side of the vertical position and tapping smartly with a rubber mallet. After the chamber has been filled and the air bubbles removed, turn off the water supply and close the fill, pressure release, and drain valves. Remove the drain line from the end of the pressure release valve. This process should be completed in 2 minutes (± 5 seconds).

8.5 Pressurize the chamber for 5 minutes (±5 seconds) by opening the pressure valve. Adjust the pressure regulator as necessary to maintain the required pressure. At about 4-3/4 minutes, close the pressure valve.

8.6 After 5 minutes (±5 seconds) of pressurization, *while wearing ear protection*, release the pressure by opening the pressure release valve as described in the equipment manufacturer's instructions.

8.7 Refill the pressure chamber by re-attaching the drain line to the pressure release valve, opening the fill valve, and turning on the water supply. Allow water to fill for approximately 30 seconds, rotating the chamber approximately 45° either side of vertical to remove any air bubbles in the chamber. Turn off the water supply, close the fill and pressure release valves, and remove the drain line.

8.8 Re-pressurize the chamber after a total elapsed time of 1 minute (±5 seconds) without pressure. Adjust the regulator as necessary to maintain the desired pressure. This pressurization time is 2 minutes (±5 seconds). At about 1-3/4 minutes, close the pressure valve.

8.9 Release the pressure after 2 minutes (±5 seconds), *while wearing ear protection*, by rapidly opening the pressure release valve (as in 8.6 above).

8.10 Repeat Steps 8.7 through 8.9 eight additional times for a total of ten pressurization cycles. Rotate the pressure chamber back to horizontal for draining.

8.11 Turn off the valve on the Nitrogen bottle and open the drain valve. Drain the water from the pressure chamber by slowly opening the pressure valve and allowing the compressed gas in the line to force the water out of the chamber.

8.12 Unbolt the chamber and remove the specimen. Dry the specimen to a constant mass at a temperature of 110°C ±5°C (230°F ±9°F), and allow it to cool at room temperature for one hour.

8.13 Place enough of the specimen into the tumbler to fill it approximately half way, and tumble for 1 minute (±5 seconds). Repeat with the remaining portion of the specimen. Separate out any pieces passing the 9.5 mm (3/8 in.) sieve but retained on the 4.75 mm (No. 4) sieve. Determine the masses of both the +9.5 mm (3/8 in.) and cumulative -9.5 mm, +4.75 mm (No. 4) sieve particles to the nearest gram. Record these values as m_i and $m4_i$ respectively for the "i" number of pressurization cycles completed. Count the number of pieces retained on the 9.5 mm (3/8 in.) sieve and record this number as n_i. Count the number of pieces passing the 9.5 mm (3/8 in.) sieve but retained on the 4.75 mm (No. 4) sieve and record the cumulative number as $n4_i$.

8.14 Repeat Steps 8.2 through 8.13 for a total of 50 pressurization cycles.

9. CALCULATIONS

9.1 *Percentage Fracture* - Calculate the percentage of fracturing after each ten pressurization cycles as follows:

$$FP_i = 100 \times (n4_i/2 + n_i - n_0)/n_0 \tag{1}$$

where FP_i is the percent fractures after "i" pressurization cycles,

$n4_i$ is the cumulative number of pieces passing the 9.5 mm (3/8 in.) sieve but retained on the 4.75 mm (No. 4) sieve after "i" pressurization cycles,

n_i is the number of pieces retained on the 9.5 mm (3/8 in.) sieve after "i" pressurization cycles, and

n_0 is the initial number of pieces tested.

Report FP values to the nearest integer.

9.2 *Hydraulic Fracture Index* - Calculate the hydraulic fracture index (HFI) as the number of cycles necessary to produce 5 percent fracturing by the following methods:

If 5 percent fracturing is achieved in 50 or fewer cycles, calculate the HFI as a linear interpolation of the number of cycles that produced 5 percent fractures:

$$HFI = A + 10 \times [(10-FP_A)/(FP_B - FP_A)] \tag{2}$$

where A is the number of cycles just prior to achieving 5 percent fracturing,

FP_A is the percentage of fracturing just prior to achieving 5 percent fracturing, and

FP_B is the percentage of fracturing just after achieving 5 percent fracturing.

If 5 percent fracturing is no achieved in 50 pressurization cycles, calculate the HFI as an extrapolation from no fracturing at 0 cycles through the amount of fracturing at 50 cycles:

$$HFI = 50 \times (5/FP_{50})$$

where FP_{50} is the percentage of fracturing after 50 pressurization cycles.

Report HFI values to the nearest integer.

9.3 *Percent Mass Loss* - Determine the percent mass loss as follows:

$$ML_i = (100/m_0) \times [m_0 - (m4_i + m_i)] \qquad (3)$$

where ML_i is the percentage of mass loss after "i" cycles of pressurization,

$m4_i$ is the cumulative mass of the material passing the 9.5 mm (3/8 in.) sieve but retained on the 4.75 mm (No. 4) sieve after "i" pressurization cycles,

m_i is the mass of the pieces retained on the 9.5 mm (3/8 in.) sieve after "i" pressurization cycles, and

m_0 is the initial mass of the specimen tested.

Report ML values to the nearest integer.

NOTE 10 - When data from more than one specimen are combined for determining final results, the raw data, m_0, n_0, $m4_i$, $n4_i$, m_i, and n_i, should be combined prior to calculation of ML_i, FP_i and HFI.

10. REPORT

10.1 The report shall include the following information and data:

10.2 *Sample Identification:*

10.2.1 Report the person or agency submitting the sample for testing.

10.2.2 List the source or identifying code for the aggregate.

10.3 *Initial Specimen Size:*

10.3.1 Report the particle size range(s) tested as determined in Section 7 of this procedure.

10.3.2 Report the initial mass and initial number of particles as determined in Step 8.1 above.

10.4 *Percentage Fracture*

Report the percentage fracture after each series of ten pressurization cycles.

10.5 *Percentage Mass Loss*

Report the percentage mass loss after each series of ten pressurization cycles.

10.6 *Hydraulic Fracture Index*

Report the hydraulic fracture index for the specimen

NOTE 11 - A graph of fracture percentage versus number of cycles is often useful in presenting the data.

NOTE 12 - Examples of a daily data sheet and a report form are shown in Appendix B.

11. PRECISION

11.1 *Within-Laboratory Precision* - The precision of results from a single aggregate source appears to depend upon the number of pieces tested. Data is currently being collected in order to determine the within-laboratory precision.

11.2 *Between Laboratory Precision* - Data is currently being collected to determine the between-laboratory precision.

Hydraulic Fracture of Coarse Aggregate

Appendix C1

Determination of Pressure Release Rate

1. PURPOSE

1.1 The purpose of this procedure is to determine the pressure release rate for the Hydraulic Fracture Apparatus.

1.2 This procedure can also be used to determine the necessary chamber pressure required to produce the specified release rate.

2. EQUIPMENT

2.1 *Pressure Transducer System* - The pressure transducer and associated power supply and signal conditioning electronics should have linearity within 3 percent over the range of 0 to the maximum pressure measured. The pressure transducer should be able to be installed into one of the threaded connections in the pressure chamber.

2.2 *Data Acquisition System* - Equipment for digitally recording the output from the pressure transducer system should have a sampling rate of at least 1,000 Hz.

3. PROCEDURE

3.1 Do not put an aggregate specimen into the pressure chamber, but otherwise close the pressure chamber and fill it with water as described in Sections 8.2 through 8.4 in the test procedure.

3.2 Pressurize the chamber to the desired pressure as described in Section 8.5.

3.3 While releasing the pressure as described in Section 8.6, digitally record the pressure-time history

3.4 Repeat the pressurization-pressure release as described in Sections 8.7 through 8.10 for a total of ten recordings of pressure-time histories.

4. ANALYSIS

4.1 Determine the pressure release rate for a 0.01 second duration for each pressure release by finding the largest pressure difference for a 0.01-second time duration. This may be accomplished by:

4.1.1 Starting at approximately the middle of the pressure-time data, determine the pressure difference for a time duration of 0.01 second, and calculate the pressure release rate.

4.1.2 Move one data point higher in pressure and re-calculate the pressure release rate as described above. Continue until a clear trend in decreasing pressure release rates is determined.

4.1.3 Starting again at the data point used in 4.1.1, above, this time move one data point lower and calculate the pressure release rate for the 0.01 second duration. Continue until a clear trend in decreasing pressure release rates is determined.

4.1.4 Sort the pressure release rates determined in 4.1.1 through 4.1.3 and determine the greatest pressure release rate for a 0.01 second duration.

4.1.5 Repeat 4.1.1 through 4.1.4 for each pressure-time history recorded.

4.1 Average the ten maximum pressure release rates determined above, and report this as the average pressure release rate for a 0.01 second duration for the chamber configuration and input pressure tested.

Hydraulic Fracture of Coarse Aggregate

Appendix C2

Sample Daily Data Sheet
and
Results Summary Form

Daily Data Sheet

Specimens Tested ____________

Specimen ID							Combined
Date Treated							
initial	m0, g						
initial	n0						
Date Pressurized							
10 Cycles	m10, g						
	m410, g						
	ML10						
	n10						
	n410						
	FP10						
Date Pressurized							
20 Cycles	m20, g						
	m420, g						
	ML20						
	n20						
	n420						
	FP20						
Date Pressurized							
30 Cycles	m30, g						
	m430, g						
	ML30						
	n30						
	n430						
	FP30						
Date Pressurized							
40 Cycles	m40, g						
	m440, g						
	ML40						
	n40						
	n440						
	FP40						
Date Pressurized							
50 Cycles	m50, g						
	m450, g						
	ML50						
	n50						
	n450						
	FP50						

Source: ____________ Submitted by: ____________ Tested by: ____________

Date Received: ____________ Size: ____________ Description: ____________

Equipment Number: ____________ Location: ____________

Configuration: Chamber psi= ____________ Solenoid psi= ____________

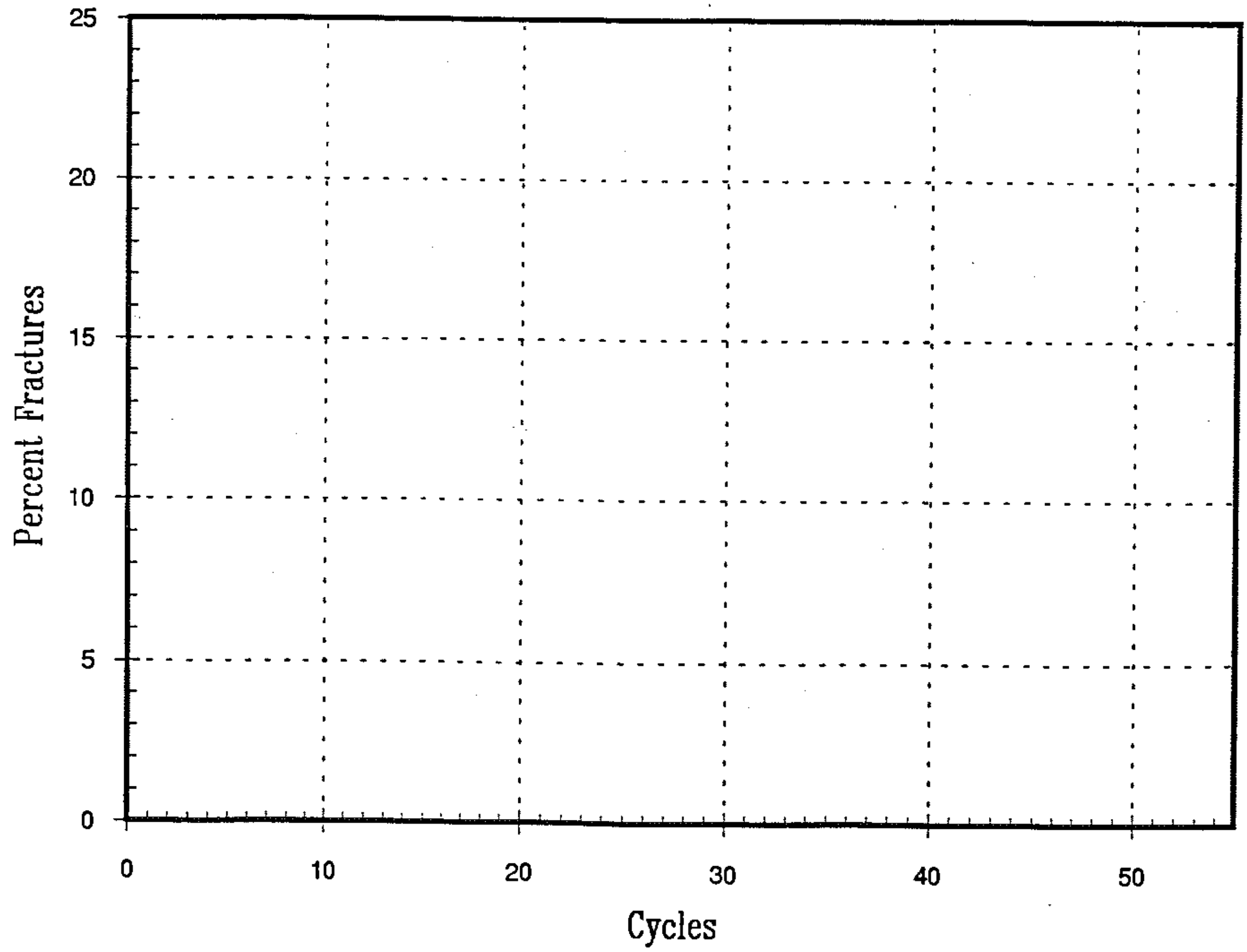
Results Summary Form

Source: Submitted by: Tested by: Date:

Size Range: Initial Mass: Initial # Particles:

Testing Date	Cumulative # of Cycles (0)	Mass (+9.5 mm)	Mass (9.5 to 4.75 mm)	Count (+9.5 mm)	Count (9.5 to 4.75 mm)	% Mass Loss	Percent Fractures
	10						
	20						
	30						
	40						
	50						

HFI=



Appendix D

Summary of Freeze-Thaw Durability Test Results

Appendix D

Summary of Freeze-Thaw Durability test Results

This appendix contains a summary of all laboratory test results for the materials tested in the freeze-thaw durability portion of this study, as well as a brief explanation of the significance of the results.

Freeze-thaw testing was performed on aggregates from all sources investigated in this study. The initial four aggregates, the control aggregates, were batched at the U of M, and tested at U of M, U of Minn, and MDOT. The purpose of this test series was to correlate the various testing machines at the different laboratories, as well as to determine any effects from operator or laboratory variability. Batches 1 to 3 of the Marblehead, Rockwood Pit #58-08, Drummond Pit #17-66, and Bundy Hill Pit #30-35 aggregates were used for this correlative testing. It should be noted that the vacuum saturation back-filling procedure used in making these batches was later found to be deficient. Thus, Pit #58-08 and Marblehead Pit #93-01 had to be rebatched using an improved procedure to get accurate expansion data. As far as correlating the testing sites, the original batches were sufficient, because all beams tested had undergone the same treatment. The expansion data used for these materials, though, was determined from later batches (Rockwood Pit #58-08 batches 7 to 9, and Marblehead Pit #93-01 batches 5 to 7) using the new vacuum saturation procedure. Rockwood Pit #58-08 batches 4 to 6 and Marblehead Pit #93-01 batch 4 were not used in the analysis and have not been reported. The difference in vacuum pressure was found not to have affected the Drummond Pit #17-66 and Bundy Hill Pit #30-35 specimens, so these materials were not rebatched.

Testing of the control aggregates showed good correlation between the test sites for all four aggregates, as shown in Table D-1. This indicates that variability between testing machines and operators was not considerable for freeze-thaw beams made at the U of M and tested at the U of M and elsewhere. In addition, because a range of aggregate durabilities was covered, this correlative study showed that precision could be maintained between labs for a large span of durabilities. The values obtained for the control aggregates led to questions about the batching procedure, though, because the results for

Rockwood Pit #58-08 and Marblehead Pit #93-01 did not match MDOT's database values. For both of these marginal durability aggregates, it was found that degree of saturation plays a major role in performance. The MTM procedure was modified to ensure that vacuum pressure was not lost during backfilling with water in the vacuum saturation procedure. This ensured a higher degree of saturation in the aggregates. When tested for freeze-thaw durability using the new procedure, the expansion approached MDOT's database values.

A recycled concrete aggregate from a paving project on Eastbound Interstate 96 (near Brighton, Michigan) further strengthened the evidence that the degree of saturation may be a major factor in the freeze-thaw performance of an aggregate. The recycled concrete aggregate is a highly porous material (absorption =5.26%). It was tested using the original vacuum saturation procedure, where pressure was lost during backfilling. Of the three batches tested, one batch met the new vacuum saturation procedure guidelines. The other two aggregates lost roughly 0.5 in.hg. of vacuum pressure during backfilling. This difference in pressure caused a significant difference in freeze-thaw expansion. The batch saturated with the new procedure expanded roughly three times as much as the other batches. For highly porous aggregates, it is believed that slight changes in vacuum pressure can significantly vary the amount of water being forced into the aggregate pores. This in turn affects the degree of saturation and freeze-thaw performance of the aggregate.

In addition to the initial four aggregates made at U of M and tested at various laboratories, MDOT made and tested three batches of the Rockwood Pit #58-08 material at it's concrete laboratory. This allowed for a comparison of the batching procedures between MDOT and U of M. These batches were used to pinpoint the problem with vacuum procedure, as well as to verify that the new procedure was effective. The data from these batches is summarized in this appendix as MDOT Rockwood Pit #58-08 batches 1 to 3. Once the correlation and refinement of batching and freeze-thaw methods were complete, the next testing phase was started.

The second set of materials tested was a group of five aggregates. Chosen because they span the range of durability, these aggregates included both natural gravels and crushed stone. These aggregates included Bruce Mine Pit #95-10, Evergreen Pit

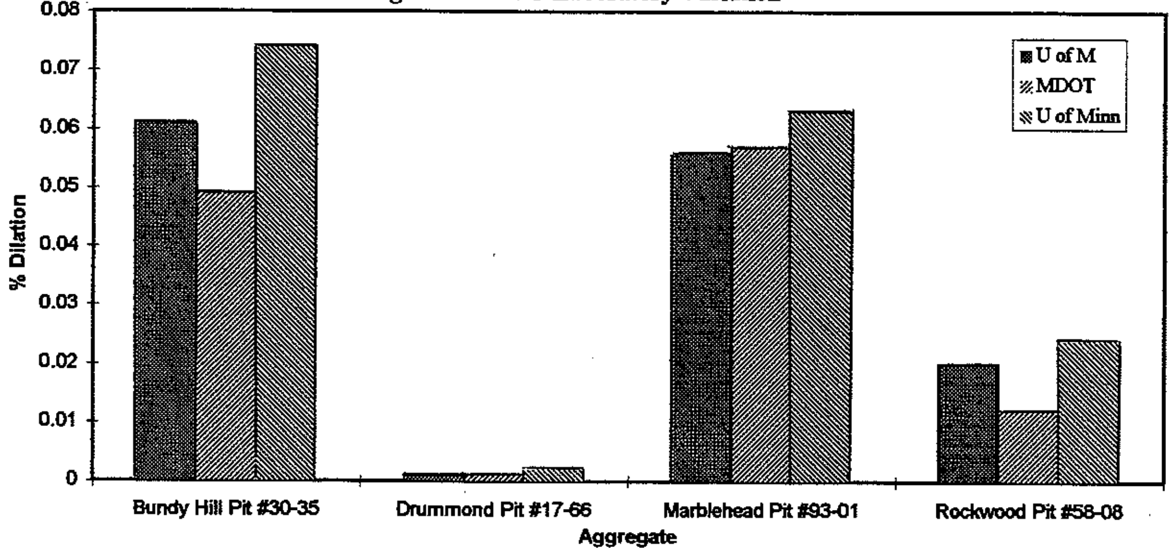
#52-78, Celotex Pit #07-20, France Silica Pit #93-03, and City Limits Pit #17-20. Three batches were made for each aggregate source, and freeze-thaw testing was performed at the U of M. Occasional batches were made with three extra beams that were sent to MDOT for testing. This allowed for a regular spot-check of the freeze-thaw results obtained by the U of M. This testing sequence gave the bulk of the data to be correlated to the WHFT procedure.

The final freeze-thaw testing phase included three aggregates from the medium durability range (Denniston Farms Pit #58-09, Michigan Foundation Pit #82-06, and Maybee Pit #58-04). It had been observed that some medium durability aggregates posed difficulty for correlations between the WHFT and freeze-thaw methods. These aggregates were tested to provide additional data to establish and refine such a correlation.

Table D-1

Control Aggregate	Dilation U of M	Dilation MDOT	Dilation U of Minn	Average Dilation	Standard Deviation
Bundy Hill Pit #30-35	0.061	0.049	0.074	0.061	0.0125
Drummond Pit #17-66	0.001	0.001	0.002	0.001	0.0006
Marblehead Pit #93-01	0.056	0.057	0.063	0.059	0.0038
Rockwood Pit #58-08	0.020	0.012	0.024	0.019	0.0061

Figure D-1 Inter-Laboratory Variation



UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Bruce Mine
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of Bruce Mine Pit #95-10

Date sampled	Date received
Source of material	
Sampled from	Quantity represented
Submitted by	
Intended use	Specification

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.81	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	0.85	Chert (%)		
Vacuum Saturation	0.92	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	87.14	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		3/21/95	3/23/95	3/28/95	
Slump (inches)		2.5	2	2	2.17
Unit weight of Concrete (pcf)		147.08	149.72	151.68	149.49
Actual Cement Content (pcy)		522	529	535	528.82
Water-cement ratio by weight		0.42	0.45	0.47	0.45
Air Content (%)		7.4	6.7	6.4	6.83
Compressive Strength (psi)	7 days	3484	3727	3432	3548
	28 days	3860	4483	4028	4124
Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.000	0.000	0.001	
	Beam 2	0.000	0.000	0.001	
	Beam 3	0.000	0.000	0.000 *	
	Average	0.000	0.000	0.001	0.000

REMARKS: Actual Value = -0.001, reported as 0.000.

TABLE D-2

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Bundy Hill
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	4/26/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of Bundy Hill Pit #30-35

Date sampled Date received

Source of material

Sampled from Quantity represented

Submitted by

Intended use Specification

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.62	Deleterious Particles (gradation range)	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	1.01	Chert (%)		
Vacuum Saturation	1.71	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	104	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		6/9/94	6/14/94	6/30/94	
Slump (inches)		3	2.5	2.5	2.67
Unit weight of Concrete (pcf)		149.68	146.78	148.10	148.19
Actual Cement Content (pcy)		529	518	522	523.01
Water-cement ratio by weight		0.44	0.44	0.44	0.44
Air Content (%)		6	7	6.3	6.43
Compressive Strength (psi)	7 days	3137	2781	3089	3002
	28 days	4830	3073	4244	4049
Freeze-Thaw Durability (% Expansion per 100 cycles) U MICH	Beam 1	0.037	0.063	0.087	
	Beam 2	0.037	0.187*	0.078	
	Beam 3	0.048	0.056	1.118*	
	Average	0.041	0.060	0.083	0.061
Freeze-Thaw Durability (% Expansion per 100 cycles) MDOT	Beam 1	0.057	0.050	0.056	
	Beam 2	0.046	0.059	0.047	
	Beam 3	0.034	0.132*	0.036	
	Average	0.046	0.055	0.046	0.049
Freeze-Thaw Durability (% Expansion per 100 cycles) U MINN	Beam 1	0.038	0.036	0.089	
	Beam 2	0.023	0.066	0.112	
	Beam 3	0.138	0.095	0.066	
	Average	0.066	0.066	0.089	0.074

REMARKS: * Indicates outlier

TABLE D-3

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Celotex
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of Celotex Pit #07-20

Date sampled Date received

Source of material

Sampled from Quantity represented

Submitted by

Intended use Specification

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.64	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	2.33	Chert (%)		
Vacuum Saturation	2.66	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	89.62	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		3/14/95	3/14/95	3/21/95	
Slump (inches)		2.5	2.25	3	2.58
Unit weight of Concrete (pcf)		141.84	145.50	143.54	143.63
Actual Cement Content (pcy)		508	520	516	514.67
Water-cement ratio by weight		0.46	0.47	0.43	0.46
Air Content (%)		8	6.3	7.5	7.27
Compressive Strength (psi)	7 days	3152	3657	3108	3306
	28 days	3247	4007	3425	3560

Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.134	0.137	0.125	
	Beam 2	0.159	0.146	0.358	
	Beam 3	0.118	0.137	0.499*	
	Average	0.137	0.140	0.241	0.173

REMARKS: * Indicates Outlier

Beams Tested at MDOT:	0.181
	0.271
	0.296
Average:	0.249

TABLE D-4

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	City Limits
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of City Limits Pit #17-20

Date sampled		Date received	
Source of material			
Sampled from		Quantity represented	
Submitted by			
Intended use		Specification	

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.68	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	0.44	Chert (%)		
Vacuum Saturation	0.87	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	90.21	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		1/19/95	1/31/95	2/14/95	
Slump (inches)		2.25	2	2	2.08
Unit weight of Concrete (pcf)		142.96	141.82	141.82	142.20
Actual Cement Content (pcy)		508	506	506	506.82
Water-cement ratio by weight		0.50	0.47	0.47	0.48
Air Content (%)		8.5	8	8	8.17
Compressive Strength (psi)	7 days	2659	3119	3163	2980
	28 days	2883	4069	3570	3507

Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.000	0.001	0.000 *	
	Beam 2	0.000	0.001	0.001	
	Beam 3	0.000	0.001	0.003	
	Average	0.000	0.001	0.001	0.001

REMARKS:

Beams tested at MDOT:	0.000 *
	0.000
	0.000
Average:	0.000

* Actual Expansion negative (reported as 0.000)

TABLE D-5

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	D. Farms
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of Denniston Farms Pit #58-09
Date sampled Date received
Source of material
Sampled from Quantity represented
Submitted by
Intended use Specification

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.57	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	2.69	Chert (%)		
Vacuum Saturation	3.86	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	86.17	

		BATCH NUMBER			
CONCRETE MIX DATA		**1**	**2**	**3**	**Average**
Date Made		8/1/95	8/3/95	8/8/95	
Slump (inches)		2.5	3	2	2.50
Unit weight of Concrete (pcf)		145.40	143.88	144.28	144.52
Actual Cement Content (pcy)		523	518	521	521.06
Water-cement ratio by weight		0.48	0.48	0.46	0.47
Air Content (%)		6.1	6.9	6.5	6.50
Compressive Strength (psi)	7 days	2811	2689	2872	2791
	28 days	3741	3221	3455	3472
Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.046	0.014	0.042	
	Beam 2	0.045	0.030	0.038	
	Beam 3	0.055	0.026	0.044	
	Average	0.049	0.023	0.041	0.038

REMARKS:

TABLE D-6

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Drummond
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	4/26/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of Drummond Pit #17-66
Date sampled Date received
Source of material
Sampled from Quantity represented
Submitted by
Intended use Specification

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.74	Deleterious Particles (gradation range)	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	0.38	Chert (%)		
Vacuum Saturation	0.58	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	98	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		6/14/94	6/30/94	7/12/94	
Slump (inches)		2	3	2.25	2.42
Unit weight of Concrete (pcf)		149.02	145.98	149.74	148.25
Actual Cement Content (pcy)		521	509	522	517.23
Water-cement ratio by weight		0.46	0.47	0.47	0.46
Air Content (%)		6.8	7.4	6.9	7.03
Compressive Strength (psi)	7 days	3933	3611	3384	3643
	28 days	4462	3808	3623	3964
Freeze-Thaw Durability (% Expansion per 100 cycles) U MICH	Beam 1	0.000	0.000	0.001	
	Beam 2	0.000	0.002	0.001	
	Beam 3	0.000	0.001	0.000	
	Average	0.000	0.001	0.001	0.001
Freeze-Thaw Durability (% Expansion per 100 cycles) MDOT	Beam 1	0.000	0.000	0.001	
	Beam 2	0.000	0.002	0.001	
	Beam 3	0.000	0.002	0.001	
	Average	0.000	0.001	0.001	0.001
Freeze-Thaw Durability (% Expansion per 100 cycles) U MINN	Beam 1	0.000	0.001	0.002	
	Beam 2	0.043*	0.000	0.002	
	Beam 3	0.007	0.000	0.006	
	Average	0.004	0.000	0.003	0.002

REMARKS: Negative dilations reported as 0.000 * Indicates Outlier

TABLE D-7

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Evergreen 52-78
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of	Evergreen Pit #52-78		
Date sampled		Date received	
Source of material			
Sampled from		Quantity represented	
Submitted by			
Intended use		Specification	

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.69	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	1.99	Chert (%)		
Vacuum Saturation	2.14	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	96.64	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		2/16/95	2/16/95	2/28/95	
Slump (inches)		2.75	3	2	2.58
Unit weight of Concrete (pcf)		146.70	147.92	146.02	146.88
Actual Cement Content (pcy)		515	521	517	517.61
Water-cement ratio by weight		0.49	0.48	0.44	0.47
Air Content (%)		7	6.5	7.2	6.90
Compressive Strength (psi)	7 days	2310	2587	3108	2668
	28 days	3625	3410	4220	3752
Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.204	0.319	0.245	
	Beam 2	0.297	0.288	0.259	
	Beam 3	0.313	0.258	0.169	
	Average	0.271	0.289	0.224	0.261

REMARKS:

Beams Tested at MDOT	0.310
	0.373
	0.308
Average:	0.330

TABLE D-8

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	France Stone 93-3
Job No.	M-DOT Freeze Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of	France Stone Pit # 93-3		
Date sampled		Date received	
Source of material			
Sampled from		Quantity represented	
Submitted by			
Intended use		Specification	

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.62	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	2.39	Chert (%)		
Vacuum Saturation	3.36	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	87.83	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		4/21/95	4/21/95	4/21/95	
Slump (inches)		3.00	2.25	2.50	2.58
Unit weight of Concrete (pcf)		143.76	145.26	144.28	144.43
Actual Cement Content (pcy)		513	519	514	515
Water-cement ratio by weight		0.47	0.46	0.48	0.47
Air Content (%)		6.5	7.3	7.4	7.1
Compressive Strength (psi)	7 days	2891	3403	2682	2992
	28 days	4253	4547	3725	4175
Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.003	0.013	0.002	
	Beam 2	0.003	0.014	0.002	
	Beam 3	0.002	0.008	0.005	
	Average	0.003	0.012	0.003	0.006

REMARKS:

TABLE D-9

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Marblehead
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of	Marblehead Pit #93-01		
Date sampled		Date received	
Source of material			
Sampled from		Quantity represented	
Submitted by			
Intended use		Specification	

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.49	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	3.28	Chert (%)		
Vacuum Saturation	4.38	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	88	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		6/21/94	6/23/94	6/28/94	
Slump (inches)		2	2.25	3	2.42
Unit weight of Concrete (pcf)		143.90	143.44	141.74	143.03
Actual Cement Content (pcy)		524	516	514	517.74
Water-cement ratio by weight		0.45	0.54	0.47	0.48
Air Content (%)		6.3	6.3	7.5	6.70
Compressive Strength (psi)	7 days	3287	3263	3608	3386
	28 days	4965	4694	4438	4699
Freeze-Thaw Durability (% Expansion per 100 cycles) U MICH	Beam 1	0.043	0.052	0.043	
	Beam 2	0.048	0.042	0.041	
	Beam 3	0.082	0.068	0.085	
	Average	0.058	0.054	0.056	0.056
Freeze-Thaw Durability (% Expansion per 100 cycles) MDOT	Beam 1	0.039	0.038	0.058	
	Beam 2	0.044	0.063	0.056	
	Beam 3	0.059	0.058	0.095	
	Average	0.047	0.053	0.070	0.057
Freeze-Thaw Durability (% Expansion per 100 cycles) U MINN	Beam 1	0.089	0.062	0.096	
	Beam 2	0.041	0.049	0.055	
	Beam 3	0.063	0.071	0.042	
	Average	0.064	0.061	0.064	0.063

TABLE D-10

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Marblehead
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of	Marblehead Pit #93-01		
Date sampled		Date received	
Source of material			
Sampled from		Quantity represented	
Submitted by			
Intended use		Specification	

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.49	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	3.28	Chert (%)		
Vacuum Saturation	4.38	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	88	

		BATCH NUMBER			
CONCRETE MIX DATA		5	6	7	Average
Date Made		3/30/95	3/30/95	4/6/95	
Slump (inches)		2	2.5	2.25	2.25
Unit weight of Concrete (pcf)		144.72	143.96	144.06	144.25
Actual Cement Content (pcy)		526	523	524	524.34
Water-cement ratio by weight		0.47	0.47	0.46	0.47
Air Content (%)		6.3	6.7	6.7	6.57
Compressive Strength (psi)	7 days	3245	2956	3423	3208
	28 days	4103	3721	4639	4155
Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.080	0.051	0.070	
	Beam 2	0.067	0.045	0.074	
	Beam 3	0.074	0.052	0.064	
	Average	0.074	0.049	0.070	0.064

REMARKS:

Beams tested at MDOT:	0.076
	0.070
	0.099
Average:	0.082

TABLE D-11

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Maybee
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of Maybee Pit #58-04

Date sampled	Date received
Source of material	
Sampled from	Quantity represented
Submitted by	
Intended use	Specification

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.44	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	3.79	Chert (%)		
Vacuum Saturation	5.31	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	82.72	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		7/27/95	8/1/95	8/3/95	
Slump (inches)		2.5	2	2	2.17
Unit weight of Concrete (pcf)		141.90	142.32	143.48	142.57
Actual Cement Content (pcy)		516	523	527	521.92
Water-cement ratio by weight		0.54	0.46	0.47	0.49
Air Content (%)		7.5	6	6.3	6.60
Compressive Strength (psi)	7 days	2633	2967	3237	2946
	28 days	3471	3708	3888	3689

Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.040	0.043	0.053	
	Beam 2	0.037	0.034	0.055	
	Beam 3	0.044	0.037	0.057	
	Average	0.040	0.038	0.055	0.044

REMARKS:

TABLE D-12

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Michigan Foundation
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of	Michigan Foundation Pit #82-06		
Date sampled		Date received	
Source of material			
Sampled from		Quantity represented	
Submitted by			
Intended use		Specification	

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.42	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	4.63	Chert (%)		
Vacuum Saturation	6.58	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	83.58	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		7/20/95	7/26/95	7/26/95	
Slump (inches)		2	2.75	3	2.58
Unit weight of Concrete (pcf)		141.86	142.40	138.96	141.07
Actual Cement Content (pcy)		518	519	508	515.25
Water-cement ratio by weight		0.48	0.49	0.47	0.48
Air Content (%)		7.1	6.4	6.1	6.53
Compressive Strength (psi)	7 days	2388	2158	2681	2409
	28 days	2998	3544	3390	3310

Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.060	0.065	0.092	
	Beam 2	0.069	0.059	0.090	
	Beam 3	0.059	0.065	0.065	
	Average	0.063	0.063	0.082	0.069

REMARKS:

TABLE D-13

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Rockwood
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	4/26/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of Rockwood Pit #58-08

Date sampled Date received

Source of material

Sampled from Quantity represented

Submitted by

Intended use Specification

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.59	Deleterious Particles (gradation range)	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	2.47	Chert (%)		
Vacuum Saturation	3.39	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	87.83	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		5/26/94	6/21/94	7/7/94	
Slump (inches)		3	2	3	2.67
Unit weight of Concrete (pcf)		144.24	142.06	142.80	143.03
Actual Cement Content (pcy)		516	508	512	511.80
Water-cement ratio by weight		0.49	0.50	0.47	0.49
Air Content (%)		6	7.6	7.4	7.00
Compressive Strength (psi)	7 days	3876	2934	3111	3307
	28 days	5211	4134	4005	4450
Freeze-Thaw Durability (% Expansion per 100 cycles) U MICH	Beam 1	0.008	0.006	0.011	
	Beam 2	0.048	0.020	0.015	
	Beam 3	0.034	0.020	0.014	
	Average	0.030	0.015	0.013	0.020
Freeze-Thaw Durability (% Expansion per 100 cycles) MDOT	Beam 1	0.037	0.002	0.007	
	Beam 2	0.004	0.004	0.004	
	Beam 3	0.038	0.004	0.005	
	Average	0.026	0.003	0.005	0.012
Freeze-Thaw Durability (% Expansion per 100 cycles) U MINN	Beam 1	0.039	0.022	0.008	
	Beam 2	0.038	0.010	0.011	
	Beam 3	0.054	0.013	0.017	
	Average	0.044	0.015	0.012	0.024

Remarks:

TABLE D-14

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Rockwood 58-8
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	UM Concrete
Date	2/29/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of	Rockwood Stone Pit #58-08		
Date sampled		Date received	
Source of material			
Sampled from		Quantity represented	
Submitted by			
Intended use		Specification	

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.59	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak	2.47	Chert (%)		
Vacuum Saturation	3.39	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	87.83	

		BATCH NUMBER			
CONCRETE MIX DATA		7	8	9	Average
Date Made		1/19/95	1/24/95	1/31/95	
Slump (inches)		3	2	2.5	2.5
Unit weight of Concrete (pcf)		140.98	144.84	142.54	142.79
Actual Cement Content (pcy)		501	519	509	509.49
Water-cement ratio by weight		0.53	0.48	0.50	0.51
Air Content (%)		8.5	7.3	8	7.93
Compressive Strength (psi)	7 days	2375	3472	3194	3014
	28 days	3141	4586	3610	3779

Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.035	0.059	0.028	
	Beam 2	0.023	0.068	0.023	
	Beam 3	0.022	0.067	0.030	
	Average	0.026	0.065	0.027	0.039

REMARKS:

TABLE D-15

MDOT
MATERIALS & TECHNOLOGY

Freeze-Thaw No.	Rockwood
Job No.	M-DOT Freeze-Thaw / WHFT
Laboratory No.	MDOT M & T
Date	9/26/95

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of	Rockwood Pit #58-08		
Date sampled		Date received	
Source of material	Rockwood stone from U of M for WHFT study		
Sampled from	Source	Quantity represented	
Submitted by	W. Hansen		
Intended use		Specification	Grade 6aa

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.57	Deleterious Particles (gradation range	1" - 3/8"	#4
Absorption (%)		Soft Particles (%)		
24 Hour Soak		Chert (%)		
Vacuum Saturation	3.89	Sum of Soft & Chert (%)		
Crushed Material in sample (%)				
Los Angeles Abrasion (% of wear)		Unit Weight of Agg. (dry, loose, pcf)	88.00	

		BATCH NUMBER			
CONCRETE MIX DATA		1	2	3	Average
Date Made		10/13/94	10/18/94	10/20/94	
Slump (inches)		2.5	2.25	3	2.58
Unit weight of Concrete (pcf)		141.28	141.20	140.34	140.94
Actual Cement Content (pcy)		506	506	503	505.00
Water-cement ratio by weight		0.49	0.49	0.48	0.49
Air Content (%)		6.9	7.5	7.6	7.33
Compressive Strength (psi)	7 days	4180	3980	3780	3980
	28 days	4960	4950	4570	4827

Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.015	0.017	0.035	
	Beam 2	0.024	0.029	0.019	
	Beam 3	0.016	0.036	0.022	
	Average	0.018	0.027	0.025	0.023

REMARKS:

TABLE D-16

UNIVERSITY OF MICHIGAN
MATERIALS DEPARTMENT

Freeze-Thaw No.	Recycled I-96
Job No.	MCPA Recycled Concrete Project
Laboratory No.	UM Concrete
Date	4/27/96

REPORT OF TEST
FREEZE-THAW DURABILITY IN CONCRETE

Report on sample of	Recycled I 96 at Brighton
Date sampled	9/15/94
Source of material	Crushing plant-Milford
Sampled from	Stockpile
Submitted by	Phil Mohr
Intended use	WHFT Study

PROPERTIES OF COARSE AGGREGATE

Bulk Specific Gravity (dry basis)	2.35
Absorption (%) by Vacuum Saturation	5.26
Unit Weight of Agg. (dry, loose, pcf)	84.39

		BATCH NUMBER			
CONCRETE MIX DATA		**1**	**2**	**3**	**Average**
Date Made		11/10/94	11/15/94	11/22/94	
Slump (inches)		2	2.5	2.75	2.42
Unit weight of Concrete (pcf)		141.82	141.02	140.60	141.15
Actual Cement Content (pcy)		530	524	524	526
Water-cement ratio by weight		0.43	0.46	0.44	0.45
Air Content (%)		6.2	6.6	8.2	7.0
Compressive Strength (psi)	7 days	4220	3435	3175	3610
	28 days	4644	4416	4726	4595

Vacuum Pressure (in-hg)*		28.0	28.6	27.4	
Freeze-Thaw Durability (% Expansion per 100 cycles)	Beam 1	0.025	0.107	0.032	
	Beam 2	0.023	0.063	0.038	
	Beam 3	0.021	0.083	0.039	
	Average	0.023	0.084	0.036	0.048

REMARKS:

*MTM specifies 28.5±0.2 in-hg of vacuum pressure.

TABLE D-17

Appendix E

Summary of Washington Hydraulic Fracture Test Results

Table E-1: Bruce Mines (Pit 95-10) 1/2"-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	4	1	1150	90	3291.9	563	4/7/95	5/12/95	10	3283.7	2.97	562	2	0.16%	0.0	469
								5/17/95	20	3279.9	2.97	562	2	0.27%	0.0	
								5/19/95	30	3277.5	3.12	563	3	0.34%	0.3	
								5/22/95	40	3276.2	3.12	563	3	0.38%	0.3	
								5/31/95	50	3270.7	5.85	563	6	0.47%	0.5	
2	4	2	1150	90	3294	562	4/7/95	6/20/95	10	3287.5	0	562	0	0.20%	0.0	234
								6/22/95	20	3282.2	0.83	562	1	0.33%	0.1	
								6/23/95	30	3277.6	1.62	562	3	0.45%	0.3	
								6/26/95	40	3275.2	2.47	564	5	0.50%	0.8	
								6/27/95	50	3271	4.37	565	6	0.57%	1.1	
2	4	3	1150	90	3305.7	560	4/7/95	7/11/95	10	3295.5	1.88	560	1	0.25%	0.1	400
								7/13/95	20	3291.2	2.81	560	2	0.35%	0.2	
								7/17/95	30	3285	2.81	559	2	0.54%	0.0	
								7/20/95	40	3281.6	4.87	560	6	0.58%	0.5	
								7/21/95	50	3280.7	4.93	560	7	0.61%	0.6	
1	1	11	1150	90	2900	450	8/10/95	8/14/95	10	2900	0	450	0	0.00%	0.0	205
								8/15/95	20	2899	1.35	450	2	-0.01%	0.2	
								8/16/95	30	2896	2.95	452	4	0.04%	0.9	
								8/18/95	40	2895	3.32	450	5	0.06%	0.6	
								8/21/95	50	2895	3.88	452	7	0.04%	1.2	
1	1	12	1150	90	2818	489	8/10/95	8/14/95	10	2817	0	489	0	0.04%	0.0	500+
								8/15/95	20	2817	0	489	0	0.04%	0.0	
								8/16/95	30	2817	0	489	0	0.04%	0.0	
								8/18/95	40	2816	0	489	0	0.07%	0.0	
								8/21/95	50	2816	0.14	489	1	0.07%	0.1	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.000	N/A	0.000	N/A	Durability Factor	100	N/A	100	N/A

Table E-2: Bruce Mines (Pit 95-10) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	4	1	1150	90	3360.6	272	4/7/95	4/28/95	10	3354.9	1.01	273	3	0.14%	0.9	194
								5/1/95	20	3349.2	1.01	273	3	0.31%	0.9	
								5/3/95	30	3348	1.01	273	3	0.34%	0.9	
								5/8/95	40	3345.3	1.01	273	3	0.43%	0.9	
								5/10/95	50	3342.7	1.01	274	3	0.50%	1.3	
2	4	2	1150	90	3330.4	268	4/7/95	6/2/95	10	3326.8	0	268	0	0.11%	0.0	447
								6/5/95	20	3323	0	268	0	0.22%	0.0	
								6/7/95	30	3319.4	0	268	0	0.33%	0.0	
								6/13/95	40	3318.1	0	268	0	0.37%	0.0	
								6/16/95	50	3314.1	1.5	268	3	0.44%	0.6	
2	4	3	1150	90	3308.3	256	4/7/95	6/20/95	10	3301	0	256	0	0.22%	0.0	142
								6/22/95	20	3294.7	0.75	256	1	0.39%	0.2	
								6/26/95	30	3285.3	3.7	256	3	0.58%	0.6	
								6/27/95	40	3282.9	4.4	258	5	0.63%	1.8	
								6/29/95	50	3280.9	4.4	258	5	0.70%	1.8	
1	1	03	1150	90	2644	200	3/29/95	4/26/95	10	2643	1	200	1	0.00%	0.3	71
								4/27/95	20	2633	4.38	202	6	0.25%	2.5	
								4/30/95	30	2630	5.82	200	8	0.31%	2.0	
								5/2/95	40	2630	5.82	200	8	0.31%	2.0	
								5/3/95	50	2626	8.02	201	12	0.38%	3.5	
1	1	04	1150	90	2668	200	3/29/95	4/26/95	10	2668	0	200	0	0.00%	0.0	143
								4/27/95	20	2667	0	200	0	0.04%	0.0	
								4/30/95	30	2666	1.02	201	1	0.04%	0.8	
								5/2/95	40	2663	2.78	201	3	0.08%	1.3	
								5/3/95	50	2662	2.78	202	3	0.12%	1.8	
1	1	05	1150	90	2916	215	6/23/95	6/28/95	10	2915	0	215	0	0.03%	0.0	500+
								6/29/95	20	2915	0	215	0	0.03%	0.0	
								7/3/95	30	2913	0	215	0	0.10%	0.0	
								7/5/95	40	2913	0	215	0	0.10%	0.0	
								7/6/95	50	2912	0	215	0	0.14%	0.0	
1	1	06	1150	90	2985	215	6/23/95	6/28/95	10	2984	0	215	0	0.03%	0.0	500+
								6/29/95	20	2982	0	215	0	0.10%	0.0	
								7/3/95	30	2981	0	215	0	0.13%	0.0	
								7/5/95	40	2981	0	215	0	0.13%	0.0	
								7/6/95	50	2980	0	215	0	0.17%	0.0	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.000	N/A	0.000	N/A	Durability Factor	100	N/A	100	N/A

Table E-3: Bundy Hill (Pit 30-35) 1/2"-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	S1	1150	90	3466	507	6/3/95	6/11/95	10	3462.2	1.65	508	4	0.06%	0.6	77
								6/12/95	20	3454.8	4.99	508	13	0.18%	1.5	
								6/13/95	30	3452	6.1	508	14	0.23%	1.6	
								6/14/95	40	3443.7	10.7	509	24	0.33%	2.8	
								6/15/95	50	3440.3	12	510	27	0.40%	3.3	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.029	0.049	0.059	0.065
Durability Factor	47	30	24	21

Table E-4: Bundy Hill (Pit 30-35) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	S1	1150	90	3443.1	210	5/10/95	5/11/95	10	3441.1	0	210	0	0.06%	0.0	45
								5/12/95	20	3439	0	210	0	0.12%	0.0	
								5/13/95	30	3437	1.35	213	3	0.14%	2.1	
								5/14/95	40	3428.7	6.11	211	12	0.24%	3.3	
								5/18/95	50	3421.5	8.51	216	17	0.38%	6.9	
2	3	S2	1150	90	3579.8	211	5/10/95	5/26/95	10	3578.9	0	211	0	0.03%	0.0	117
								6/11/95	20	3576.7	0.15	212	1	0.08%	0.7	
								6/12/95	30	3572.4	1.75	213	4	0.16%	1.9	
								6/13/95	40	3571.3	1.85	212	5	0.19%	1.7	
								6/14/95	50	3569	1.85	213	5	0.25%	2.1	
1	1	21	1150	90	2982	180	4/6/95	4/7/95	10	2981	1.16	181	3	-0.01%	1.4	75
								4/10/95	20	2976	2.77	181	6	0.11%	2.2	
								4/11/95	30	2975	2.77	181	6	0.14%	2.2	
								4/12/95	40	2975	2.99	182	7	0.13%	3.1	
								4/13/95	50	2973	3.21	182	8	0.19%	3.3	
1	1	22	1150	90	3090	185	4/6/95	4/7/95	10	3088	0	186	0	0.06%	0.5	93
								4/10/95	20	3088	0	186	0	0.06%	0.5	
								4/11/95	30	3087	0	189	0	0.10%	2.2	
								4/12/95	40	3086	0	189	0	0.13%	2.2	
								4/13/95	50	3083	1.78	189	2	0.17%	2.7	
1	1	23	1150	90	3049	185	4/6/95	4/7/95	10	3048	0	186	0	0.03%	0.5	154
								4/10/95	20	3047	0	186	0	0.07%	0.5	
								4/11/95	30	3046	0.38	186	1	0.09%	0.8	
								4/12/95	40	3045	0.69	186	3	0.11%	1.4	
								4/13/95	50	3042	1.42	186	4	0.18%	1.6	
1	1	24	1150	90	2974	180	4/6/95	4/7/95	10	2973	0.24	180	1	0.03%	0.3	180
								4/10/95	20	2972	0.45	180	2	0.05%	0.6	
								4/11/95	30	2971	0.45	180	2	0.09%	0.6	
								4/12/95	40	2969	1.1	180	3	0.13%	0.8	
								4/13/95	50	2968	1.1	181	3	0.16%	1.4	
1	1	25	1150	90	2937	180	UT	5/2/95	10	2937	0	180	0	0.00%	0.0	300
								5/3/95	20	2934	1.79	180	2	0.04%	0.6	
								5/5/95	30	2932	1.79	180	2	0.11%	0.6	
								5/6/95	40	2931	1.79	180	2	0.14%	0.6	
								5/9/95	50	2931	1.9	180	3	0.14%	0.8	

Table E-4: Bundy Hill (Pit 30-35) 3/4"-1" (cont)

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
1	1	26	1150	90	3265	180	UT	5/2/95	10	3263	0.6	180	1	0.04%	0.3	64
								5/3/95	20	3261	0.6	180	1	0.10%	0.3	
								5/5/95	30	3260	0.94	182	2	0.12%	1.7	
								5/6/95	40	3259	1.6	184	4	0.13%	3.3	
								5/9/95	50	3257	2.31	184	6	0.17%	3.9	
1	1	27	1150	90	3198	190	6/27/95	6/29/95	10	3194	2.12	192	5	0.06%	2.4	29
								7/3/95	20	3186	7.94	193	6	0.13%	3.2	
								7/4/95	30	3183	10.57	193	25	0.14%	8.2	
								7/5/95	40	3182	10.57	193	25	0.17%	8.2	
								7/6/95	50	3182	10.57	194	25	0.17%	8.7	
1	1	28	1150	90	3219	190	6/27/95	6/29/95	10	3217	0	190	0	0.06%	0.0	119
								7/3/95	20	3215	1.17	192	4	0.09%	2.1	
								7/4/95	30	3214	1.17	192	4	0.12%	2.1	
								7/5/95	40	3213	1.17	192	4	0.15%	2.1	
								7/6/95	50	3213	1.17	192	4	0.15%	2.1	
1	1	29	1150	90	3254	190	6/28/95	7/3/95	10	3254	0	190	0	0.00%	0.0	500+
								7/4/95	20	3253	0	190	0	0.03%	0.0	
								7/5/95	30	3253	0	190	0	0.03%	0.0	
								7/6/95	40	3252	0	190	0	0.06%	0.0	
								7/7/95	50	3251	0	190	0	0.09%	0.0	
1	1	30	1150	90	3229	190	6/28/95	7/3/95	10	3228	0.44	190	1	0.02%	0.3	119
								7/4/95	20	3228	0.44	190	1	0.02%	0.3	
								7/5/95	30	3226	1.25	192	2	0.05%	1.6	
								7/6/95	40	3226	1.25	192	2	0.05%	1.6	
								7/7/95	50	3225	1.25	193	2	0.09%	2.1	
1	1	31	1150	90	3286	190	6/28/95	7/3/95	10	3285	0	190	0	0.03%	0.0	500+
								7/5/95	20	3285	0	190	0	0.03%	0.0	
								7/6/95	30	3285	0	190	0	0.03%	0.0	
								7/7/95	40	3284	0	190	0	0.06%	0.0	
								7/10/95	50	3284	0	190	0	0.06%	0.0	
1	1	32	1150	90	3270	190	6/28/95	7/3/95	10	3268	0.59	190	1	0.04%	0.3	190
								7/5/95	20	3268	0.59	190	1	0.04%	0.3	
								7/6/95	30	3267	0.59	191	1	0.07%	0.8	
								7/7/95	40	3265	1.3	191	3	0.11%	1.3	
								7/10/95	50	3265	1.3	191	3	0.11%	1.3	

Table E-4: Bundy Hill (Pit 30-35) 3/4"-1" (cont)

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
1	1	33	1150	90	3320	190	7/6/95	7/7/95	10	3317	0.78	190	1	0.07%	0.3	79
								7/10/95	20	3315	3	190	4	0.06%	1.1	
								7/11/95	30	3313	3.51	190	5	0.11%	1.3	
								7/12/95	40	3308	7.72	190	10	0.13%	2.6	
								7/13/95	50	3307	8.75	190	12	0.13%	3.2	
1	1	34	1150	90	3288	190	7/6/95	7/7/95	10	3286	0	190	0	0.06%	0.0	63
								7/10/95	20	3285	0.82	190	2	0.07%	0.5	
								7/11/95	30	3281	3.38	193	7	0.11%	3.4	
								7/12/95	40	3279	4.26	193	9	0.14%	3.9	
								7/13/95	50	3278	4.26	193	9	0.17%	3.9	
1	1	35	1150	90	3269	190	7/6/95	7/7/95	10	3267	0	190	0	0.06%	0.0	106
								7/10/95	20	3267	0	190	0	0.06%	0.0	
								7/11/95	30	3260	3.12	190	9	0.18%	2.4	
								7/12/95	40	3259	3.12	190	9	0.21%	2.4	
								7/13/95	50	3258	3.12	190	9	0.24%	2.4	
1	1	36	1150	90	3339	190	7/6/95	7/7/95	10	3337	0	192	0	0.06%	1.1	95
								7/10/95	20	3333	4.2	191	5	0.05%	1.8	
								7/11/95	30	3332	4.2	191	5	0.08%	1.8	
								7/12/95	40	3330	4.2	192	5	0.14%	2.4	
								7/13/95	50	3329	5.43	192	6	0.14%	2.6	
2	8	1	1150	90	3001.9	176	7/28/95	8/1/95	10	3001.2	0	177	0	0.02%	0.6	88
								8/2/95	20	2993.8	0	177	0	0.27%	0.6	
								8/3/95	30	2985.7	0	178	0	0.54%	1.1	
								8/7/95	40	2992.9	2.44	178	4	0.22%	2.3	
								8/8/95	50	2990.3	3.49	178	6	0.27%	2.8	
2	8	2	1150	90	2999.2	186	7/28/95	8/1/95	10	2997.1	0	187	0	0.07%	0.5	78
								8/2/95	20	2993.3	1.77	187	4	0.14%	1.6	
								8/3/95	30	2992.4	1.77	187	4	0.17%	1.6	
								8/7/95	40	2994.7	2.22	187	5	0.08%	1.9	
								8/8/95	50	2988.4	2.66	189	6	0.27%	3.2	
2	8	3	1150	90	3146.4	197	7/28/95	8/1/95	10	3145.7	0.22	198	1	0.02%	0.8	62
								8/3/95	20	3134.4	5.86	197	11	0.20%	2.8	
								8/4/95	30	3127.3	6.94	198	12	0.39%	3.6	
								8/8/95	40	3123	9.1	197	16	0.45%	4.1	
								8/9/95	50	3121.4	9.1	197	16	0.51%	4.1	

Table E-4: Bundy Hill (Pit 30-35) 3/4"-1" (cont)

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	8	4	1150	90	3008	187	7/28/95	8/2/95	10	2992.5	0	187	0	0.52%	0.0	134
								8/3/95	20	2984.8	0.19	187	1	0.76%	0.3	
								8/4/95	30	3003.1	0.19	188	1	0.16%	0.8	
								8/8/95	40	3002.1	0.19	189	1	0.19%	1.3	
								8/9/95	50	3000	0.85	189	3	0.24%	1.9	
2	8	5	1150	90	3012.9	182	7/28/95	8/2/95	10	2997.9	0	182	0	0.50%	0.0	70
								8/3/95	20	2986.2	0.45	182	2	0.87%	0.5	
								8/7/95	30	3003.5	0.89	183	3	0.28%	1.4	
								8/8/95	40	2999.4	2.24	183	7	0.37%	2.5	
								8/9/95	50	2994.9	4.98	183	11	0.43%	3.6	
9	7	6	1150	90	2916	215	7/28/95	8/1/95	10	3015.4	0	186	0	0.50%	-0.5	500+
								8/2/95	20	3025.7	0.2	186	1	0.16%	-0.3	
								8/3/95	30	3022.8	1.28	186	2	0.22%	0.0	
								8/4/95	40	3021.7	1.28	186	2	0.25%	0.0	
								8/7/95	50	3021.6	1.28	186	2	0.26%	0.0	
9	7	7	1150	90	3024.8	179	7/28/95	8/1/95	10	3020.4	0.7	179	3	0.12%	0.8	128
								8/2/95	20	3018.1	0.7	179	3	0.20%	0.8	
								8/3/95	30	3014.4	1.63	179	6	0.29%	1.7	
								8/4/95	40	3013.3	1.63	179	6	0.33%	1.7	
								8/8/95	50	3011.7	1.99	179	7	0.37%	2.0	
9	7	8	1150	90	3016.9	185	7/28/95	8/1/95	10	3001.4	3.36	186	10	0.40%	3.2	17
								8/2/95	20	2991.1	5.24	187	17	0.68%	5.7	
								8/3/95	30	2994.3	7.02	187	19	0.52%	6.2	
								8/7/95	40	2991.6	8.36	186	20	0.56%	5.9	
								8/8/95	50	2990	8.36	187	20	0.61%	6.5	
9	7	9	1150	90	3004.2	179	7/28/95	8/1/95	10	3002.3	0	179	0	0.06%	0.0	149
								8/2/95	20	2996	1.82	179	2	0.21%	0.6	
								8/3/95	30	2997.6	1.82	180	2	0.16%	1.1	
								8/7/95	40	2996	1.82	180	2	0.21%	1.1	
								8/8/95	50	2995.6	1.82	181	2	0.23%	1.7	
9	7	10	1150	90	3005	175	7/28/95	8/2/95	10	3002.2	0	175	0	0.09%	0.0	500+
								8/3/95	20	3002	0	175	0	0.10%	0.0	
								8/7/95	30	3001.4	0	175	0	0.12%	0.0	
								8/8/95	40	3000.1	0	175	0	0.16%	0.0	
								8/9/95	50	2999.2	0	175	0	0.19%	0.0	

Table E-4: Bundy Hill (Pit 30-35) 3/4"-1" (cont)

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	4	11	1150	90	3203.9	179	8/20/95	8/31/95	10	3202.4	0	179	0	0.05%	0.0	112
								9/5/95	20	3200.5	0	179	0	0.11%	0.0	
								9/6/95	30	3198.7	0	180	0	0.16%	0.6	
								9/7/95	40	3195.9	0.3	180	1	0.24%	0.8	
								9/8/95	50	3194.1	0.93	181	4	0.28%	2.2	
2	4	12	1150	90	2891.9	180	8/20/95	8/31/95	10	2878.7	1.13	180	3	0.42%	0.8	300
								9/1/95	20	2871.3	1.13	180	3	0.67%	0.8	
								9/5/95	30	2868.4	1.13	180	3	0.77%	0.8	
								9/6/95	40	2866.6	1.13	180	3	0.84%	0.8	
								9/7/95	50	2865.5	1.13	180	3	0.87%	0.8	
2	4	13	1150	90	3165	180	8/20/95	8/31/95	10	3141.3	5.6	179	11	0.57%	2.5	20
								9/5/95	20	3136.4	6.41	182	14	0.70%	5.0	
								9/6/95	30	3128.3	9.18	183	22	0.87%	7.8	
								9/7/95	40	3111.9	17.85	179	35	1.11%	9.2	
								9/8/95	50	3109.4	18.28	179	41	1.18%	10.8	
9	4	14	1150	90	3229.9	180	8/20/95	8/31/95	10	3226.6	0	180	0	0.10%	0.0	INF
								9/5/95	20	3225	0	180	0	0.15%	0.0	
								9/6/95	30	3224	0	180	0	0.18%	0.0	
								9/7/95	40	3222.8	0	180	0	0.22%	0.0	
								9/8/95	50	3222	0	180	0	0.24%	0.0	
9	4	15	1150	90	3024.9	180	8/20/95	8/31/95	10	3023.4	0	181	0	0.05%	0.6	150
								9/5/95	20	3021.7	0.6	181	1	0.09%	0.8	
								9/6/95	30	3019.6	0.6	182	1	0.16%	1.4	
								9/7/95	40	3018.1	0.85	182	2	0.20%	1.7	
								9/7/95	50	3017.6	0.85	182	2	0.21%	1.7	
9	4	16	1150	90	3086.4	180	8/27/95	8/31/95	10	3084.1	0	181	0	0.07%	0.6	450
								9/1/95	20	3073.4	0	180	0	0.42%	0.0	
								9/5/95	30	3072	0	180	0	0.47%	0.0	
								9/6/95	40	3070.2	0	181	0	0.52%	0.6	
								9/7/95	50	3068.6	0	181	0	0.58%	0.6	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.029	0.049	0.059	0.065	Durability Factor	47	30	24	21

Table E-5: Celotex (Pit 7-36) 1/2"-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	4	1	1150	90	3280.9	572	4/5/95	5/12/95	10	3260.6	5.14	571	12	0.46%	0.9	99
								5/15/95	20	3240.8	8.64	569	15	0.96%	0.8	
								5/17/95	30	3236.5	8.87	570	17	1.08%	1.1	
								5/19/95	40	3234.5	9.37	570	21	1.13%	1.5	
								5/22/95	50	3232.4	10.75	572	29	1.15%	2.5	
2	4	2	1150	90	3305.4	517	4/5/95	6/20/95	10	3293.3	1.15	518	2	0.33%	0.4	78
								6/22/95	20	3285.2	7.77	520	13	0.38%	1.8	
								6/26/95	30	3274	10.37	520	17	0.64%	2.2	
								6/27/95	40	3264.5	15.29	521	24	0.77%	3.1	
								6/29/95	50	3258.7	17.99	518	31	0.87%	3.2	
2	4	3	1150	90	3324.5	578	4/5/95	6/27/95	10	3308.9	5.33	578	9	0.31%	0.8	131
								6/29/95	20	3299.7	9.14	574	14	0.47%	0.5	
								7/6/95	30	3290.2	10.62	577	18	0.71%	1.4	
								7/11/95	40	3287.1	12.42	577	21	0.75%	1.6	
								7/13/95	50	3286.2	13.15	577	24	0.76%	1.9	
1	1	11	1150	90	2805	500	8/15/95	8/16/95	10	2796	3.25	500	9	0.20%	0.9	109
								8/17/95	20	2787	9.1	500	19	0.32%	1.9	
								8/18/95	30	2778	15.39	499	23	0.41%	2.1	
								8/21/95	40	2778	15.39	499	23	0.41%	2.1	
								8/22/95	50	2777	15.39	500	23	0.45%	2.3	
1	1	12	1150	90	3051	500	8/15/95	8/16/95	10	3046	0	502	0	0.16%	0.4	119
								8/17/95	20	3040	3.3	501	6	0.25%	0.8	
								8/18/95	30	3035	4.57	501	10	0.37%	1.2	
								8/21/95	40	3033	4.57	502	10	0.44%	1.4	
								8/22/95	50	3029	6.68	502	17	0.50%	2.1	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.193	N/A	0.201	N/A	Durability Factor	2	N/A	2	N/A

Table E-6: Celotex (Pit 7-36) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	4	1	1150	90	3296.6	234	4/5/95	4/28/95	10	3292	0.57	235	1	0.12%	0.6	84
								5/1/95	20	3282.2	2.28	235	6	0.37%	1.7	
								5/3/95	30	3280.4	2.28	236	6	0.42%	2.1	
								5/8/95	40	3274.4	4.25	237	8	0.54%	3.0	
								5/10/95	50	3272.1	4.25	237	8	0.61%	3.0	
2	4	2	1150	90	3252.2	230	4/5/95	5/22/95	10	3250.2	1.84	232	5	0.00%	2.0	55
								6/7/95	20	3243	3.79	234	8	0.17%	3.5	
								6/13/95	30	3240.4	4.26	234	10	0.23%	3.9	
								6/16/95	40	3235.7	5.93	233	12	0.33%	3.9	
								6/19/95	50	3229.5	6.65	234	13	0.49%	4.6	
2	4	3	1150	90	3291	227	4/5/95	6/7/95	10	3283.8	0.42	230	1	0.21%	1.5	47
								6/12/95	20	3280.3	2.09	229	4	0.26%	1.8	
								6/14/95	30	3275.4	3.64	230	7	0.36%	2.9	
								6/16/95	40	3274.7	4.24	231	9	0.37%	3.7	
								6/19/95	50	3269.3	5.94	233	13	0.48%	5.5	
1	1	3	1150	90	2870	200	5/3/95	5/6/95	10	2868	0	202	0	0.07%	1.0	71
								5/8/95	20	2864	1.42	202	3	0.16%	1.8	
								5/9/95	30	2863	1.76	203	4	0.18%	2.5	
								5/10/95	40	2859	2.12	204	5	0.31%	3.3	
								5/16/95	50	2858	2.43	204	6	0.33%	3.5	
1	1	4	1150	90	2790	200	5/3/95	5/6/95	10	2789	0	200	0	0.04%	0.0	125
								5/8/95	20	2787	0.44	201	1	0.09%	0.8	
								5/9/95	30	2786	0.44	201	1	0.13%	0.8	
								5/10/95	40	2783	1	202	2	0.22%	1.5	
								5/16/95	50	2783	2.43	203	2	0.16%	2.0	
1	1	5	1150	90	2968	205	6/22/95	6/23/95	10	2966	0	205	0	0.07%	0.0	500+
								6/26/95	20	2964	0	205	0	0.13%	0.0	
								6/27/95	30	2962	0	205	0	0.20%	0.0	
								6/28/95	40	2961	0	206	0	0.24%	0.5	
								6/29/95	50	2959	0	206	0	0.30%	0.5	
1	1	6	1150	90	2978	205	6/22/95	6/23/95	10	2966	4.9	206	15	0.24%	4.1	64
								6/26/95	20	2964	5.7	205	16	0.28%	3.9	
								6/27/95	30	2961	6.89	204	18	0.34%	3.9	
								6/28/95	40	2960	6.89	204	18	0.37%	3.9	
								6/29/95	50	2958	6.89	204	18	0.44%	3.9	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.193	N/A	0.201	N/A	Durability Factor	2	N/A	2	N/A

Table E-7: City Limits (Pit 17-20) 1/2"-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	4	1	1150	90	3296.7	539	4/5/95	5/12/95	10	3292.1	1.7	538	4	0.09%	0.2	108
								5/17/95	20	3285.6	1.7	542	4	0.29%	0.9	
								5/19/95	30	3257.8	9.25	539	16	0.90%	1.5	
								5/22/95	40	3249.8	13.28	537	24	1.02%	1.9	
								5/23/95	50	3244.2	17.11	536	31	1.07%	2.3	
2	4	1	1150	90	3257.9	487	4/5/95	6/22/95	10	3250.2	2.24	485	4	0.17%	0.0	122
								6/27/95	20	3242.4	3.88	485	6	0.36%	0.2	
								6/28/95	30	3235.7	4	487	11	0.56%	1.1	
								6/29/95	40	3223	7.42	484	20	0.84%	1.4	
								7/10/95	50	3215.9	8.85	485	24	1.02%	2.1	
2	4	1	1150	90	3272.8	544	4/5/95	7/11/95	10	3263.3	5.03	542	8	0.14%	0.4	94
								7/13/95	20	3258.3	6.55	542	12	0.24%	0.7	
								7/17/95	30	3281.1	6.55	545	12	-0.45%	1.3	
								7/19/95	40	3270.1	9.11	546	17	-0.20%	1.9	
								7/20/95	50	3265.5	11.2	548	21	-0.12%	2.7	
1	1	13	1150	90	3041	550	8/15/95	8/21/95	10	3040	0	550	0	0.03%	0.0	500+
								8/22/95	20	3036	0.9	550	2	0.13%	0.2	
								8/23/95	30	3034	1.8	549	3	0.17%	0.1	
								8/24/95	40	3028	2.93	549	5	0.33%	0.3	
								9/5/95	50	3026	3.98	549	7	0.36%	0.5	
1	1	14	1150	90	3141	530	8/15/95	8/21/95	10	3137	0.96	530	2	0.10%	0.2	331
								8/22/95	20	3132	2.19	529	5	0.22%	0.3	
								8/23/95	30	3130	2.19	529	5	0.28%	0.3	
								8/24/95	40	3127	2.19	530	5	0.38%	0.5	
								9/5/95	50	3122	4.08	530	8	0.48%	0.8	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.003	N/A	0.001	N/A	Durability Factor	93	N/A	98	N/A

Table E-8: City Limits (Pit 17-20) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	4	1	1150	90	3294.7	233	4/5/95	4/28/95	10	3275.7	N/A	230	5	0.58%	-0.2	65
								5/1/95	20	3269.6	N/A	227	8	0.76%	-0.9	
								5/3/95	30	3262.2	N/A	230	12	0.99%	1.3	
								5/8/95	40	3258.3	N/A	230	18	1.10%	2.6	
								5/10/95	50	3253.6	N/A	231	22	1.25%	3.9	
2	4	2	1150	90	3272.7	218	4/5/95	6/2/95	10	3268.3	0.36	218	1	0.12%	0.2	55
								6/7/95	20	3256.2	4.33	220	9	0.37%	3.0	
								6/13/95	30	3246	9.76	219	12	0.52%	3.2	
								6/14/95	40	3244.4	9.76	221	12	0.57%	4.1	
								6/16/95	50	3238.8	10.86	221	14	0.70%	4.6	
2	4	3	1150	90	3296.8	216	4/5/95	6/12/95	10	3291.4	2	216	5	0.10%	1.2	43
								6/14/95	20	3283.7	2.59	216	7	0.32%	1.6	
								6/19/95	30	3275.2	4.67	218	13	0.51%	3.9	
								6/21/95	40	3270.3	6.33	218	15	0.61%	4.4	
								6/22/95	50	3258.8	7.79	221	19	0.92%	6.7	
1	1	3	1150	90	2741	200	3/29/95	4/17/95	10	2741	0	200	0	0.00%	0.0	200
								4/18/95	20	2739	0	200	0	0.07%	0.0	
								4/19/95	30	2727	2.34	199	3	0.43%	0.3	
								4/20/95	40	2725	3.18	199	4	0.47%	0.5	
								4/21/95	50	2723	4.88	199	7	0.48%	1.3	
1	1	4	1150	90	2945	200	3/29/95	4/17/95	10	2944	0.2	200	1	0.03%	0.3	77
								4/18/95	20	2940	0.91	200	2	0.14%	0.5	
								4/19/95	30	2934	1.97	201	4	0.31%	1.5	
								4/20/95	40	2926	6.89	201	10	0.41%	3.0	
								4/21/95	50	2924	7.2	201	11	0.47%	3.3	
1	1	5	1150	90	3112	220	6/20/95	6/21/95	10	3108	0.5	221	1	0.11%	0.7	183
								6/22/95	20	3107	0.5	221	1	0.14%	0.7	
								6/23/95	30	3105	0.5	221	1	0.21%	0.7	
								6/24/95	40	3102	1.98	221	4	0.26%	1.4	
								6/25/95	50	3101	1.98	221	4	0.29%	1.4	
1	1	6	1150	90	3213	225	6/20/95	6/21/95	10	3209	1	227	3	0.09%	1.6	54
								6/22/95	20	3207	1.67	228	5	0.13%	2.4	
								6/23/95	30	3204	2.45	228	7	0.20%	2.9	
								6/24/95	40	3200	4.87	229	12	0.25%	4.4	
								6/25/95	50	3196	6.7	228	15	0.32%	4.7	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.003	N/A	0.001	N/A	Durability Factor	93	N/A	98	N/A

Table E-9: Dennison Farms (Pit 58-09) 1/2"-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results										
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	1	1150	90	2909.8	494	7/14/95	7/24/95	10	2907	1.09	495	3	0.06%	0.5	112
								7/26/95	20	2904	3.05	495	8	0.09%	1.0	
								7/31/95	30	2894.8	5.86	495	11	0.31%	1.3	
								8/1/95	40	2884.6	9.76	494	16	0.53%	1.6	
								8/2/95	50	2879.1	13.07	494	22	0.61%	2.2	
2	3	2	1150	90	3186.1	545	7/14/95	7/22/95	10	3181.2	0.86	545	5	0.13%	0.5	124
								7/24/95	20	2904	1.18	545	7	8.82%	0.6	
								7/26/95	30	3226.5	1.98	545	10	-1.33%	0.9	
								7/28/95	40	3173	2.38	545	17	0.34%	1.6	
								7/31/95	50	3165.2	4.88	546	20	0.50%	2.0	
2	4	3	1150	90	2845.3	473	7/14/95	7/24/95	10	2841.5	0.18	475	1	0.13%	0.5	237
								7/26/95	20	2835.5	0.86	476	3	0.31%	1.0	
								7/27/95	30	2831.6	1.86	475	4	0.42%	0.8	
								8/1/95	40	2824.7	3.6	475	5	0.60%	1.0	
								8/4/95	50	2825.3	3.97	475	6	0.56%	1.1	
1	1	11	1150	90	2982	500	8/2/95	8/3/95	10	2982	0	500	0	0.00%	0.0	500
								8/7/95	20	2980	0.17	500	1	0.06%	0.1	
								8/8/95	30	2980	0.17	500	1	0.06%	0.1	
								8/9/95	40	2977	0.92	500	3	0.14%	0.3	
								8/10/95	50	2976	0.92	501	3	0.17%	0.5	
1	1	12	1150	90	2785	500	8/2/95	8/3/95	10	2782	0.18	501	1	0.10%	0.3	417
								8/7/95	20	2781	0.18	501	1	0.14%	0.3	
								8/8/95	30	2780	0.18	501	1	0.17%	0.3	
								8/9/95	40	2778	0.82	501	3	0.22%	0.5	
								8/10/95	50	2776	1.22	501	4	0.28%	0.6	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.020	N/A	N/A	N/A	Durability Factor	60	N/A	N/A	N/A

Table E-10: Dennison Farms (Pit 58-09) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	1	1150	90	3091.5	240	7/14/95	7/15/95	10	3088.6	0.69	240	2	0.07%	0.4	240
								7/16/95	20	3085.7	0.69	241	2	0.17%	0.8	
								7/17/95	30	3083.2	1.29	240	3	0.23%	0.6	
								7/18/95	40	3081.6	1.29	241	3	0.28%	1.0	
								7/19/95	50	3080.3	1.29	241	3	0.32%	1.0	
2	4	2	1150	90	3139.2	247	7/14/95	7/20/95	10	3134.9	0.66	248	1	0.12%	0.6	137
								7/24/95	20	3130.2	0.66	248	1	0.27%	0.6	
								7/25/95	30	3128.1	0.66	249	1	0.33%	1.0	
								7/26/95	40	3102.2	1.26	249	3	1.14%	1.4	
								7/27/95	50	3098.6	1.98	249	5	1.23%	1.8	
2	4	3	1150	90	3204.8	245	7/14/95	7/19/95	10	3201.3	1.25	246	2	0.07%	0.8	56
								7/21/95	20	3196.9	1.4	247	3	0.20%	1.4	
								7/24/95	30	3192.4	1.98	247	4	0.33%	1.6	
								7/25/95	40	3186.8	4.6	248	8	0.42%	2.9	
								7/26/95	50	3183.5	6.63	250	12	0.46%	4.5	
1	1	1	1150	90	2729	208	7/21/95	7/22/95	10	2728	0	209	0	0.04%	0.5	149
								7/24/95	20	2726	0	211	0	0.11%	1.4	
								7/25/95	30	2725	0	211	0	0.15%	1.4	
								7/26/95	40	2722	2.46	209	2	0.17%	1.0	
								7/27/95	50	2720	2.82	210	3	0.23%	1.7	
1	1	2	1150	90	2648	205	7/21/95	7/22/95	10	2646	0	205	0	0.08%	0.0	256
								7/24/95	20	2645	0	205	0	0.11%	0.0	
								7/25/95	30	2643	0	206	0	0.19%	0.5	
								7/26/95	40	2639	3.5	205	3	0.21%	0.7	
								7/27/95	50	2635	5.05	205	4	0.30%	1.0	
1	1	3	1150	90	2590	200	7/25/95	7/27/95	10	2588	0.25	200	1	0.07%	0.3	167
								7/28/95	20	2587	0.25	200	1	0.11%	0.3	
								7/30/95	30	2586	0.42	201	2	0.14%	1.0	
								8/1/95	40	2585	0.42	202	2	0.18%	1.5	
								8/2/95	50	2584	0.42	202	2	0.22%	1.5	
1	1	4	1150	90	2575	200	7/25/95	7/27/95	10	2574	0	200	0	0.04%	0.0	200
								7/28/95	20	2572	0	200	0	0.12%	0.0	
								7/31/95	30	2572	0	200	0	0.12%	0.0	
								8/1/95	40	2570	0	201	0	0.19%	0.5	
								8/2/95	50	2569	1.19	202	1	0.19%	1.3	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.020	N/A	N/A	N/A	Durability Factor	60	N/A	N/A	N/A

Table E-11: Drummond (Pit 17-66) 1/2"-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	5	2	1150	90	3524.9	687	3/30/95	4/21/95	10	3518	4.1	685	2	0.08%	-0.1	500+
								4/24/95	20	3510.7	10.1	684	7	0.12%	0.1	
								4/25/95	30	3509.9	10.1	684	7	0.14%	0.1	
								4/28/95	40	3504.9	14	681	11	0.17%	-0.1	
								5/4/95	50	3504.9	14.56	681	12	0.15%	0.0	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.005	0.001	0.001	0.002	Durability Factor	89	98	98	95

Table E-12: Drummond (Pit 17-66) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results										
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	5	2	1150	90	3512	281	3/29/95	3/29/95	10	3510.7	0	279	0	0.04%	-0.7	176
								3/30/95	20	3509.1	0	280	0	0.08%	-0.4	
								4/18/95	30	3507.3	0.5	280	2	0.12%	0.0	
								4/21/95	40	3506.2	1	282	4	0.14%	1.1	
								4/24/95	50	3504.9	1	283	4	0.17%	1.4	
1	1	9	1150	90	2706	200	7/14/95	7/18/95	10	2706	0	200	0	0.00%	0.0	500
								7/19/95	20	2705	0	201	0	0.04%	0.5	
								7/20/95	30	2703	0	201	0	0.11%	0.5	
								7/21/95	40	2700	1.98	200	2	0.15%	0.5	
								7/22/95	50	2700	1.98	200	2	0.15%	0.5	
1	1	10	1150	90	3005	210	7/14/95	7/18/95	10	3004	0	210	0	0.03%	0.0	350
								7/19/95	20	3004	0	211	0	0.03%	0.5	
								7/20/95	30	3002	0	211	0	0.10%	0.5	
								7/21/95	40	3001	0.68	211	1	0.11%	0.7	
								7/22/95	50	3000	0.68	211	1	0.14%	0.7	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.005	0.001	0.001	0.002	Durability Factor	89	98	98	95

Table E-13: Evergreen (Pit 52-78) 1/2'-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	4	1	1150	90	3302	528	4/7/95	4/28/95	10	3290.3	N/A	529	16	0.37%	1.7	73
								5/1/95	20	3278	N/A	527	20	0.74%	1.7	
								5/3/95	30	3271.6	N/A	526	27	0.94%	2.2	
								5/8/95	40	3265.2	15.25	526	32	0.67%	2.7	
								5/11/95	50	3258.7	18.26	527	38	0.78%	3.4	
2	4	2	1150	90	3266.7	500	4/7/95	6/22/95	10	3261.9	0.33	502	1	0.14%	0.5	167
								6/26/95	20	3250.4	1.48	502	5	0.45%	0.9	
								6/27/95	30	3247.5	1.48	502	5	0.54%	0.9	
								6/28/95	40	3239	3.47	502	7	0.74%	1.1	
								6/29/95	50	3237	4.37	503	9	0.78%	1.5	
2	4	3	1150	90	3298.9	528	4/7/95	6/29/95	10	3287.4	1.58	529	4	0.30%	0.6	189
								7/6/95	20	3281	2.23	528	5	0.48%	0.5	
								7/10/95	30	3275.4	3.54	528	9	0.61%	0.9	
								7/12/95	40	3265.9	4.87	528	12	0.85%	1.1	
								7/14/95	50	3263.9	6.48	528	14	0.86%	1.3	
1	1	11	1150	90	3145	470	8/9/95	8/10/95	10	3141	1.28	472	2	0.09%	0.6	147
								8/11/95	20	3139	1.28	472	2	0.15%	0.6	
								8/14/95	30	3138	1.5	473	3	0.17%	1.0	
								8/15/95	40	3137	2.1	473	4	0.19%	1.1	
								8/16/95	50	3136	2.1	476	4	0.22%	1.7	
1	1	12	1150	90	3117	450	8/10/95	8/10/95	10	3115	0.74	452	2	0.04%	0.7	150
								8/11/95	20	3112	0.74	452	2	0.14%	0.7	
								8/14/95	30	3110	2.52	454	5	0.14%	1.4	
								8/15/95	40	3110	2.52	454	5	0.14%	1.4	
								8/16/95	50	3106	4.72	454	7	0.20%	1.7	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.069	N/A	0.261	N/A	Durability Factor	19	N/A	2	N/A

Table E-14: Evergreen (Pit 52-78) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	4	1	1150	90	3306.6	201	4/7/95	5/12/95	10	3302.6	2.37	201	1	0.05%	0.2	50
								5/15/95	20	3293.1	4.44	203	4	0.27%	2.0	
								5/17/95	30	3286.2	6.86	206	7	0.41%	4.2	
								5/19/95	40	N/A	N/A	205	12	NA	5.0	
								5/22/95	50	N/A	N/A	205	12	N/A	5.0	
2	4	2	1150	90	3340	188	4/7/95	6/2/95	10	3312	3	188	7	0.75%	1.9	46
								6/7/95	20	3304.6	4.53	188	11	0.92%	2.9	
								6/12/95	30	3298	7.64	187	16	1.03%	3.7	
								6/15/95	40	3297.3	7.64	188	16	1.05%	4.3	
								6/19/95	50	3294.5	9.35	189	19	1.08%	5.6	
2	4	3	1150	90	3290.6	198	4/7/95	7/6/95	10	3264.6	1.43	200	4	0.75%	2.0	46
								7/10/95	20	3253.4	2.15	197	6	1.07%	1.0	
								7/11/95	30	3251.6	2.15	197	6	1.12%	1.0	
								7/12/95	40	3248.9	3.33	199	9	1.17%	2.8	
								7/14/95	50	3244	6.45	202	18	1.22%	6.6	
1	1	1	1150	90	3173	175	5/23/95	5/26/95	10	3171	0.35	175	2	0.05%	0.6	292
								5/30/95	20	3169	0.35	175	2	0.12%	0.6	
								5/31/95	30	3166	0.35	175	2	0.21%	0.6	
								6/7/95	40	3166	1.06	175	3	0.19%	0.9	
								6/8/95	50	3164	1.06	175	3	0.25%	0.9	
1	1	2	1150	90	2884	175	5/23/95	5/26/95	10	2882	0	176	0	0.07%	0.6	88
								5/30/95	20	2880	0	177	0	0.14%	1.1	
								6/1/95	30	2878	0	177	0	0.21%	1.1	
								6/7/95	40	2878	0	179	0	0.21%	2.3	
								6/8/95	50	2878	0	180	0	0.21%	2.9	
1	1	3	1150	90	3215	180	6/20/95	6/21/95	10	3215	0	180	0	0.00%	0.0	500+
								6/22/95	20	3213	0.22	180	1	0.06%	0.3	
								6/23/95	30	3211	0.22	180	1	0.12%	0.3	
								6/26/95	40	3211	0.22	180	1	0.12%	0.3	
								6/27/95	50	3210	0.22	180	1	0.15%	0.3	
1	1	4	1150	90	3042	180	6/20/95	6/21/95	10	3042	0	180	0	0.00%	0.0	82
								6/22/95	20	3039	1.26	180	2	0.06%	0.6	
								6/23/95	30	3035	3.14	180	5	0.13%	1.4	
								6/26/95	40	3035	3.14	181	5	0.13%	1.9	
								6/27/95	50	3035	3.14	183	5	0.13%	3.1	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.069	N/A	0.261	N/A	Durability Factor	19	N/A	2	N/A

Table E-14: Evergreen (Pit 52-78) 3/4"-1" (cont)

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
1	1	G	1150	90	3240	180	N/A	11/9/95	10	3233	0.00	180	0	0.20%	0.0	41
								11/10/95	20	3232	0.00	182	0	0.20%	1.1	
								11/12/95	30	3229	1.38	181	1	0.30%	0.8	
								11/13/95	40	3221	3.33	186	5	0.50%	4.7	
								11/14/95	50	3218	4.83	187	11	0.50%	6.9	
1	1	H	1150	90	3143	180	N/A	11/9/95	10	3143	7.31	182	20	0.30%	6.7	8
								11/10/95	20	3124	7.31	181	20	0.40%	6.1	
								11/12/95	30	3120	10.35	180	28	0.40%	7.8	
								11/13/95	40	3118	10.35	180	28	0.50%	7.8	
								11/14/95	50	3117	10.82	180	29	0.50%	8.1	
1	1	I	1150	90	3052	180	N/A	11/9/95	10	3046	0.00	180	0	0.20%	0.0	76
								11/10/95	20	3044	0.00	180	0	0.30%	0.0	
								11/12/95	30	3042	0.00	181	0	0.30%	0.6	
								11/13/95	40	3042	0.51	183	2	0.30%	2.2	
								11/14/95	50	3039	1.65	184	4	0.40%	3.3	
2	4	A	1150	150	2996	180	10/28/96	10/30/95	10	2975	3.65	182	11	0.60%	4.2	23
								10/31/96	20	2969	7.53	180	16	0.60%	4.4	
								11/1/96	30	2971	7.53	184	16	0.60%	6.7	
								11/2/96	40	2965	11.3	181	21	0.70%	6.4	
								11/3/96	50	2962	11.3	181	21	0.80%	6.4	
2	4	B	1150	150	3039	180	10/28/96	10/30/95	10	3035	0.48	180	2	0.10%	0.6	69
								10/31/96	20	3028	1.33	182	3	0.30%	1.9	
								11/1/96	30	3027	1.33	182	3	0.30%	1.9	
								11/2/96	40	3025	3.97	182	6	0.30%	2.8	
								11/3/96	50	3024	4.16	183	7	0.40%	3.6	
2	4	4	1150	90	3972	180	10/7/96	10/9/96	10	2972	2.55	183	5	0.50%	3.1	26
								10/10/96	20	2956	2.98	184	6	0.60%	3.9	
								10/11/96	30	2952	8.00	184	13	0.70%	5.8	
								10/12/96	40	2936	10.18	187	18	0.90%	8.9	
								10/13/96	50	2933	11.25	188	20	0.90%	10.0	
2	4	5	1150	90	3729	204	10/7/96	10/9/96	10	3717	2.89	204	6	0.20%	1.5	23
								10/10/96	20	3712	5.34	207	11	0.30%	4.2	
								10/11/96	30	3703	7.06	211	14	0.50%	6.9	
								10/12/96	40	3696	8.94	213	16	0.60%	8.3	
								10/13/96	50	3685	18.24	214	32	0.70%	12.7	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.069	N/A	0.261	N/A	Durability Factor	19	N/A	2	N/A

Table E-14: Evergreen (Pit 52-78) 3/4"-1" (cont)

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
9	4	C	1150	100	2755	180	10/28/96	10/30/96	10	2749	0.92	183	2	0.20%	2.2	57
								10/31/96	20	2745	2.99	183	8	0.30%	3.9	
								11/1/96	30	2746	2.99	183	8	0.20%	3.9	
								11/2/96	40	2745	2.99	184	8	0.20%	4.4	
								11/3/96	50	2743	2.99	184	8	0.30%	4.4	
9	4	D	1150	100	3038	180	10/28/96	10/30/96	10	3038	2.39	184	4	0.30%	3.3	19
								10/31/96	20	3028	5.36	184	11	0.40%	5.3	
								11/1/96	30	3018	8.19	186	18	0.40%	8.3	
								11/2/96	40	3015	8.86	186	19	0.40%	8.6	
								11/3/96	50	3012	10.73	187	23	0.50%	10.3	
9	4	4	1150	90	3211	180	10/7/96	10/9/96	10	3199	1.50	179	4	0.30%	0.6	37
								10/10/96	20	3195	1.50	180	4	0.40%	1.1	
								10/11/96	30	3189	3.97	181	10	0.50%	3.3	
								10/12/96	40	3181	7.94	182	17	0.70%	5.8	
								10/13/96	50	3180	7.94	183	17	0.70%	6.4	
9	4	6	1150	90	3233	210	10/7/96	10/9/96	10	3433	0	212	0	0.10%	1.0	66
								10/10/96	20	3427	0	213	0	0.20%	1.4	
								10/11/96	30	3423	1.74	214	4	0.20%	2.9	
								10/12/96	40	3420	3.55	214	7	0.30%	3.6	
								10/13/96	50	3418	4.55	214	8	0.30%	3.8	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.069	N/A	0.261	N/A	Durability Factor	19	N/A	2	N/A

Table E-15: France Stone (Pit 93-3) 1/2"-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	1	1150	90	3021.5	600	34892	34901	10	3017	0	600	0	0.15%	0.0	500+
								34904	20	3014.4	0	600	0	0.23%	0.0	
								34906	30	3013.2	0	600	0	0.27%	0.0	
								34908	40	3010	0	600	0	0.38%	0.0	
								34911	50	3008.5	0	601	0	0.43%	0.2	
2	3	2	1150	90	3038	616	34892	34904	10	3034.5	0	616	0	0.12%	0.0	500+
								34906	20	3032.2	0.17	616	1	0.19%	0.1	
								34908	30	3029.6	0.17	616	1	0.27%	0.1	
								34911	40	3027.8	0.62	616	2	0.32%	0.2	
								34912	50	3022.9	1.78	616	4	0.44%	0.3	
2	4	3	1150	90	3035.9	613	34892	34905	10	3021	2	612	2	0.42%	0.0	500+
								34906	20	3016.5	2	613	2	0.57%	0.2	
								34907	30	3009.7	2.21	614	3	0.79%	0.4	
								34912	40	3003.2	2.21	615	3	1.00%	0.6	
								34914	50	2993.9	3.49	614	4	1.27%	0.5	
1	1	11	1150	90	2740	500	34921	34922	10	2738	0	501	0	0.07%	0.2	500+
								34925	20	2736	0	502	0	0.15%	0.4	
								34926	30	2735	0	502	0	0.18%	0.4	
								34927	40	2733	0	502	0	0.26%	0.4	
								34928	50	2735	0	502	0	0.18%	0.4	
1	1	12	1150	90	2912	480	34921	34922	10	2910	0	480	0	0.07%	0.0	500+
								34925	20	2908	0.36	480	2	0.12%	0.2	
								34926	30	2906	0.36	480	2	0.19%	0.2	
								34927	40	2904	0.36	480	2	0.26%	0.2	
								34928	50	2904	0.36	480	2	0.26%	0.2	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.006	N/A	0.006	N/A	Durability Factor	86	N/A	86	N/A

Table E-16: France Stone (Pit 93-3) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	1	1150	90	3091.6	250	7/10/95	7/17/95	10	3088.4	0.14	250	1	0.10%	0.2	104
								7/18/95	20	3084.4	0.59	252	3	0.21%	1.4	
								7/19/95	30	3080.8	1.49	252	5	0.30%	1.8	
								7/20/95	40	3076.5	3.89	252	8	0.36%	2.4	
								7/21/95	50	3074.1	3.89	252	8	0.44%	2.4	
2	3	2	1150	90	3095.5	256	7/10/95	7/14/95	10	3092.9	0	256	0	0.08%	0.0	500+
								7/17/95	20	3091.3	0	256	0	0.14%	0.0	
								7/18/95	30	3089.2	0	256	0	0.20%	0.0	
								7/19/95	40	3087.3	0.1	256	1	0.26%	0.2	
								7/20/95	50	3085.7	0.1	256	1	0.31%	0.2	
2	4	3	1150	90	3110.2	253	7/10/95	7/18/95	10	3107.6	0.27	253	1	0.07%	0.2	97
								7/19/95	20	3102.8	0.27	253	1	0.23%	0.2	
								7/20/95	30	3099.7	0.49	253	2	0.32%	0.4	
								7/21/95	40	3098.7	0.79	256	4	0.34%	2.0	
								7/23/95	50	3095.5	1.07	257	5	0.44%	2.6	
1	1	3	1150	90	2570	210	5/8/95	5/10/95	10	2570	0	210	0	0.00%	0.0	500+
								5/16/95	20	2569	0	210	0	0.04%	0.0	
								5/17/95	30	2566	0.2	210	1	0.15%	0.2	
								5/18/95	40	2565	0.2	210	1	0.19%	0.2	
								5/22/95	50	2564	0.2	210	1	0.23%	0.2	
1	1	4	1150	90	2533	210	5/8/95	5/10/95	10	2532	0	210	0	0.04%	0.0	500+
								5/16/95	20	2531	0	210	0	0.08%	0.0	
								5/17/95	30	2529	0	210	0	0.16%	0.0	
								5/18/95	40	2527	1.48	210	1	0.18%	0.2	
								5/22/95	50	2525	1.48	210	1	0.26%	0.2	
1	1	5	1150	90	2826	225	6/23/95	6/27/95	10	2823	0	225	0	0.11%	0.0	500+
								6/28/95	20	2822	0	225	0	0.14%	0.0	
								6/29/95	30	2820	0	225	0	0.21%	0.0	
								7/3/95	40	2819	0	225	0	0.25%	0.0	
								7/4/95	50	2817	0	226	0	0.32%	0.4	
1	1	6	1150	90	2648	225	6/23/95	6/27/95	10	2646	0	225	0	0.08%	0.0	500+
								6/28/95	20	2643	0	225	0	0.19%	0.0	
								6/29/95	30	2643	0	225	0	0.19%	0.0	
								7/3/95	40	2641	0	225	0	0.26%	0.0	
								7/4/95	50	2641	0	225	0	0.26%	0.0	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.006	N/A	0.006	N/A	Durability Factor	86	N/A	86	N/A

Table E-17: Marblehead (Pit 93-1) 1/2"-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	5	1	1150	90	3184.8	584	3/30/95	4/21/95	10	3180.3	0	584	0	0.14%	0.0	500+
								4/24/95	20	3182	0	585	0	0.09%	0.2	
								4/25/95	30	3180.2	0	585	0	0.14%	0.2	
								4/28/95	40	3178.4	0	584	0	0.20%	0.0	
								5/4/95	50	3176.9	0	585	0	0.25%	0.2	
2	6	1	1150	90	3096.4	597	5/10/95	5/28/95	10	3088.4	0	597	0	0.26%	0.0	500+
								6/11/95	20	3085.4	0.44	597	1	0.34%	0.1	
								6/12/95	30	3082.6	0.44	597	1	0.45%	0.1	
								6/13/95	40	3081.4	0.44	597	1	0.47%	0.1	
								6/14/95	50	3079.5	0.44	597	1	0.53%	0.1	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.075	0.059	0.057	0.067	Durability Factor	17	24	25	20

Table E-18: Marblehead (Pit 93-1) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	2	1150	90	3149.5	243	3/3/95	3/20/95	10	3146.4	0	243	0	0.10%	0.0	500+
								3/21/95	20	3144.6	0	243	0	0.16%	0.0	
								3/22/95	30	3142.2	0	243	0	0.23%	0.0	
								3/23/95	40	3140.2	0.16	243	1	0.29%	0.2	
								3/27/95	50	3138.1	0.16	243	1	0.36%	0.2	
2	3	3	1150	90	3073.5	239	3/20/95	3/20/95	10	3069.5	0	239	0	0.13%	0.0	299
								3/21/95	20	3067.7	0	239	0	0.19%	0.0	
								3/22/95	30	3066.5	0	239	0	0.23%	0.0	
								3/29/95	40	3064.3	1.32	241	2	0.26%	1.3	
								3/30/95	50	3062.2	1.32	240	2	0.32%	0.8	
1	1	13	1150	90	2597	210	4/17/95	4/18/95	10	2596	0	210	0	0.04%	0.0	500+
								4/19/95	20	2594	0	210	0	0.12%	0.0	
								4/20/95	30	2593	0	210	0	0.15%	0.0	
								4/21/95	40	2592	0	210	0	0.19%	0.0	
								4/24/95	50	2592	0	210	0	0.19%	0.0	
1	1	14	1150	90	2607	210	4/17/95	4/18/95	10	2605	0	210	0	0.08%	0.0	500+
								4/19/95	20	2604	0	210	0	0.12%	0.0	
								4/20/95	30	2602	0.45	210	1	0.17%	0.2	
								4/21/95	40	2601	0.45	210	1	0.21%	0.2	
								4/24/95	50	2600	0.45	210	1	0.25%	0.2	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.075	0.059	0.057	0.067	Durability Factor	17	24	25	20

Table E-19: Maybee (Pit 58-04) 1/2"-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	1	1150	90	2986.1	550	7/17/95	7/28/95	10	2983.8	0	550	0	0.08%	0.0	275
								7/31/95	20	2980.7	0	550	0	0.18%	0.0	
								8/1/95	30	2977.1	0.66	550	2	0.28%	0.2	
								8/2/95	40	2972	1.6	550	4	0.42%	0.4	
								8/4/95	50	2970.1	3.3	551	8	0.43%	0.9	
2	4	2	1150	90	3022.1	515	7/17/95	8/2/95	10	3008.1	0.16	519	1	0.47%	0.9	286
								8/4/95	20	3005	0.42	519	2	0.57%	1.0	
								8/5/95	30	3001.6	0.42	519	2	0.68%	1.0	
								8/7/95	40	2997.1	0.42	519	2	0.83%	1.0	
								8/8/95	50	2991.2	0.89	518	3	1.01%	0.9	
2	4	3	1150	90	3034.4	520	7/17/95	8/2/95	10	3021.2	0	520	0	0.44%	0.0	500+
								8/4/95	20	3013	1.15	520	2	0.67%	0.2	
								8/5/95	30	3009.5	1.15	520	2	0.78%	0.2	
								8/7/95	40	3005.3	1.15	519	2	0.92%	0.0	
								8/8/95	50	3001.3	1.15	519	2	1.05%	0.0	
1	1	11	1150	90	2702	450	8/9/95	8/10/95	10	2690	0	450	0	0.44%	0.0	500+
								8/11/95	20	2688	0	450	0	0.52%	0.0	
								8/14/95	30	2687	0	450	0	0.56%	0.0	
								8/15/95	40	2685	0	450	0	0.63%	0.0	
								8/16/95	50	2683	0	450	0	0.70%	0.0	
1	1	12	1150	90	2780	430	8/9/95	8/10/95	10	2771	0	430	0	0.32%	0.0	500+
								8/11/95	20	2768	0	430	0	0.43%	0.0	
								8/14/95	30	2766	0	431	0	0.50%	0.2	
								8/15/95	40	2765	0	431	0	0.54%	0.2	
								8/16/95	50	2763	0	431	0	0.61%	0.2	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.053	N/A	N/A	N/A	Durability Factor	27	N/A	N/A	N/A

Table E-20: Maybee (Pit 58-04) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results										
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	1	1150	90	2921.5	223	7/17/95	7/19/95	10	2917.2	0	224	0	0.15%	0.4	139
								7/20/95	20	2914.1	0	224	0	0.25%	0.4	
								7/21/95	30	2911.7	0	224	0	0.34%	0.4	
								7/22/95	40	2909	0	225	0	0.43%	0.9	
								7/24/95	50	2902.3	3.05	225	4	0.55%	1.8	
2	4	2	1150	90	3027.2	232	7/17/95	7/24/95	10	3021.6	0	232	0	0.18%	0.0	387
								7/25/95	20	3017.4	0	232	0	0.32%	0.0	
								7/26/95	30	3010.2	0	232	0	0.56%	0.0	
								8/1/95	40	2999.1	0.83	232	1	0.90%	0.2	
								8/2/95	50	2996.4	0.83	233	1	0.99%	0.6	
2	4	3	1150	90	3084.5	229	7/17/95	7/25/95	10	3073.1	0.66	229	2	0.35%	0.4	127
								7/26/95	20	3064.3	0.66	229	2	0.63%	0.4	
								7/27/95	30	3056.1	0.66	229	2	0.90%	0.4	
								8/2/95	40	3049.7	0.66	229	2	1.11%	0.4	
								8/4/95	50	3043	1.28	231	5	1.30%	2.0	
1	1	1	1150	90	2653	200	7/25/95	7/26/95	10	2650	0	200	0	0.11%	0.0	500
								7/27/95	20	2648	0	200	0	0.19%	0.0	
								7/28/95	30	2646	0	200	0	0.26%	0.0	
								7/31/95	40	2645	0.19	200	1	0.29%	0.3	
								8/1/95	50	2643	0.39	200	2	0.36%	0.5	
1	1	2	1150	90	2679	200	7/25/95	7/26/95	10	2676	0	200	0	0.11%	0.0	500+
								7/27/95	20	2673	0	200	0	0.22%	0.0	
								7/28/95	30	2671	0	200	0	0.30%	0.0	
								34911	40	2670	0	200	0	0.34%	0.0	
								34912	50	2668	0	200	0	0.41%	0.0	
1	1	3	1150	90	2550	200	34905	34906	10	2548	0	200	0	0.08%	0.0	500
								34907	20	2546	0	200	0	0.16%	0.0	
								34908	30	2543	0.43	200	1	0.26%	0.3	
								34911	40	2542	0.59	200	2	0.29%	0.5	
								34912	50	2540	0.59	200	2	0.37%	0.5	
1	1	4	1150	90	2625	200	34905	34906	10	2623	0	201	0	0.08%	0.5	333
								34907	20	2620	0	201	0	0.19%	0.5	
								34908	30	2618	0.23	201	1	0.26%	0.8	
								34911	40	2617	0.23	201	1	0.30%	0.8	
								34912	50	2615	0.23	201	1	0.37%	0.8	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.053	N/A	N/A	N/A	Durability Factor	27	N/A	N/A	N/A

Table E-21: Michigan Foundation (Pit 82-06) 1/2"-3/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	1	1150	90	3039.9	490	7/12/95	7/26/95	10	3019.6	0.3	490	1	0.66%	0.1	500+
								7/31/95	20	3011.6	0.3	490	1	0.92%	0.1	
								8/1/95	30	3006.9	0.64	490	2	1.06%	0.2	
								8/3/95	40	3004.2	1.59	490	4	1.12%	0.4	
								8/4/95	50	2997.5	3.85	488	6	1.27%	0.2	
2	4	2	1150	90	3075.1	500	7/12/95	8/2/95	10	3065.1	2.39	499	6	0.25%	0.4	100
								8/4/95	20	3052.8	2.39	501	6	0.65%	0.8	
								8/5/95	30	3044.9	3.83	502	8	0.86%	1.2	
								8/7/95	40	3030.8	7.46	503	14	1.20%	2.0	
								8/8/95	50	3015.4	8.96	504	17	1.65%	2.5	
2	4	3	1150	90	3093.8	513	7/12/95	8/2/95	10	3081.5	1.36	514	1	0.35%	0.3	117
								8/3/95	20	3077.2	3.16	514	3	0.43%	0.5	
								8/4/95	30	3062.4	4.59	515	5	0.87%	0.9	
								8/7/95	40	3056.1	5.07	517	7	1.05%	1.5	
								8/8/95	50	3046.2	6.32	519	10	1.33%	2.1	
1	1	11	1150	90	2789	420	8/8/95	8/9/95	10	2784	0	420	0	0.18%	0.0	78
								8/10/95	20	2779	0.23	420	1	0.35%	0.1	
								8/11/95	30	2768	4.59	421	10	0.59%	1.4	
								8/14/95	40	2758	7.23	421	15	0.85%	2.0	
								8/15/95	50	2744	11.9	422	23	1.19%	3.2	
1	1	12	1150	90	2658	420	8/8/95	8/9/95	10	2654	0	420	0	0.15%	0.0	350
								8/10/95	20	2648	1.05	420	1	0.34%	0.1	
								8/11/95	30	2644	1.46	419	3	0.47%	0.1	
								8/14/95	40	2639	1.92	420	5	0.64%	0.6	
								8/15/95	50	2633	3.19	419	8	0.82%	0.7	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.048	N/A	0.063	N/A	Durability Factor	30	N/A	22	N/A

Table E-22: Michigan Foundation (Pit 82-06) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results										
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	2	1150	90	2964.1	200	7/14/95	7/15/95	10	2958	0	200	0	0.21%	0.0	71
								7/17/95	20	2954.5	0	200	0	0.32%	0.0	
								7/18/95	30	2946.9	2.44	201	3	0.50%	1.3	
								7/19/95	40	2943.2	3.69	203	7	0.58%	3.3	
								7/21/95	50	2939.5	3.8	203	8	0.70%	3.5	
2	3	3	1150	90	3000.75	195	7/10/95	7/14/95	10	2991.4	2.6	199	4	0.22%	3.1	54
								7/17/95	20	2982.9	4.6	200	6	0.44%	4.1	
								7/18/95	30	2979.5	5.6	200	7	0.52%	4.4	
								7/19/95	40	2977.2	5.6	200	7	0.60%	4.4	
								7/20/95	50	2973.9	5.93	200	8	0.70%	4.6	
2	4	4	1150	90	3068.9	209	7/10/95	7/18/95	10	3062.9	1.28	212	1	0.15%	1.7	80
								7/19/95	20	3054.9	2.86	211	3	0.36%	1.7	
								7/20/95	30	3046.8	2.86	211	3	0.63%	1.7	
								7/21/95	40	3043.6	3.89	211	5	0.70%	2.2	
								7/23/95	50	3032.6	6.52	210	11	0.97%	3.1	
1	1	2	1150	90	2608	170	7/21/95	7/25/95	10	2605	0.47	171	1	0.10%	0.9	94
								7/26/95	20	2603	0.47	172	1	0.17%	1.5	
								7/27/95	30	2599	0.47	173	1	0.33%	2.1	
								7/28/95	40	2596	0.73	173	2	0.43%	2.4	
								7/31/95	50	2594	1.47	173	3	0.48%	2.6	
1	1	3	1150	90	2582	170	7/21/95	7/25/95	10	2580	0	170	0	0.08%	0.0	106
								7/26/95	20	2577	0	170	0	0.19%	0.0	
								7/27/95	30	2573	0	170	0	0.35%	0.0	
								7/28/95	40	2569	1.03	170	1	0.46%	0.3	
								7/31/95	50	2564	3.12	171	6	0.58%	2.4	
1	1	4	1150	90	2519	170	7/25/95	7/28/95	10	2515	0	170	0	0.16%	0.0	65
								7/30/95	20	2513	0.48	171	1	0.22%	0.9	
								7/31/95	30	2510	0.48	171	1	0.34%	0.9	
								8/1/95	40	2503	3.09	172	6	0.51%	2.9	
								8/2/95	50	2496	4.28	172	9	0.74%	3.8	
1	1	4	1150	90	2549	170	7/25/95	7/28/95	10	2545	0	171	0	0.16%	0.6	142
								7/30/95	20	2545	0	171	0	0.16%	0.6	
								7/31/95	30	2541	0	171	0	0.31%	0.6	
								8/1/95	40	2539	0.23	171	2	0.38%	1.2	
								8/2/95	50	2538	0.23	172	2	0.42%	1.8	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.048	N/A	0.063	N/A	Durability Factor	30	N/A	22	N/A

Table E-23: Rockwood (Pit 58-8) 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	5	2	1150	90	2823	214	3/29/95	3/29/95	10	2818.4	2.23	214	2	0.10%	0.5	71
								3/30/95	20	2815.5	3.35	215	7	0.16%	2.1	
								4/4/95	30	2814.1	3.51	217	8	0.21%	3.3	
								4/18/95	40	2812.5	3.51	217	8	0.26%	3.3	
								4/20/95	50	2810.3	3.6	217	9	0.34%	3.5	
1	2	45	1150	85	2679	200	3/11/95	3/12/95	10	2677	0	200	0	0.07%	0.0	125
								3/13/95	20	2674	2.15	200	3	0.11%	0.8	
								3/14/95	30	2671	2.61	201	4	0.20%	1.5	
								3/15/95	40	2668	2.61	202	4	0.31%	2.0	
								3/16/95	50	2667	2.61	202	4	0.35%	2.0	
1	2	46	1150	85	2766	200	3/11/95	3/12/95	10	2762	1.3	202	4	0.10%	2.0	40
								3/13/95	20	2760	1.55	204	5	0.16%	3.3	
								3/14/95	30	2757	1.99	204	7	0.25%	3.8	
								3/15/95	40	2750	4.51	203	14	0.42%	5.0	
								3/16/95	50	2747	5.62	205	18	0.48%	7.0	
1	2	47	1150	85	2814	200	3/11/95	3/12/95	10	2810	0	201	0	0.14%	0.5	167
								3/13/95	20	2807	0	201	0	0.25%	0.5	
								3/14/95	30	2806	0.79	201	1	0.26%	0.8	
								3/15/95	40	2803	1.5	201	2	0.34%	1.0	
								3/16/95	50	2801	2.47	201	4	0.37%	1.5	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.039	N/A	0.039	N/A	Durability Factor	38	N/A	37	N/A

Table E-24: Rockwood (Pit 58-8) 3/4"-1 1/4"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
1	1	41	1150	90	2614	200	9/12/95	9/13/95	10	2612	0	200	0	0.08%	0.0	167
								9/15/95	20	2610	0.5	201	2	0.13%	1.0	
								9/19/95	30	2610	0.8	201	3	0.12%	1.3	
								9/20/95	40	2607	0.8	201	3	0.24%	1.3	
								9/21/95	50	2605	2	201	4	0.27%	1.5	
1	1	42	1150	90	2647	200	9/12/95	9/13/95	10	2642	0.6	200	1	0.17%	0.3	200
								9/15/95	20	2641	0.6	200	1	0.20%	0.3	
								9/19/95	30	2638	1.6	200	3	0.28%	0.8	
								9/20/95	40	2638	1.6	200	3	0.28%	0.8	
								9/21/95	50	2635	3.1	200	5	0.34%	1.3	
1	1	43	1150	90	2760	200	9/12/95	9/13/95	10	2757	0	200	0	0.11%	0.0	333
								9/15/95	20	2756	0.2	200	1	0.14%	0.3	
								9/19/95	30	2748	1.1	200	3	0.39%	0.8	
								9/20/95	40	2746	1.1	200	3	0.47%	0.8	
								9/21/95	50	2745	1.1	200	3	0.50%	0.8	
1	1	44	1150	90	2598	200	9/12/95	9/13/95	10	2596	0	200	0	0.08%	0.0	333
								9/15/95	20	2594	0.8	200	3	0.12%	0.8	
								9/19/95	30	2593	0.8	200	3	0.16%	0.8	
								9/20/95	40	2591	0.8	200	3	0.24%	0.8	
								9/21/95	50	2591	0.8	200	3	0.24%	0.8	
1	1	45	1150	90	2685	200	9/12/95	9/13/95	10	2682	1.1	200	2	0.07%	0.5	125
								9/15/95	20	2680	1.1	200	2	0.15%	0.5	
								9/19/95	30	2680	1.1	200	2	0.15%	0.5	
								9/20/95	40	2678	1.1	201	2	0.22%	1.0	
								9/21/95	50	2677	1.3	202	4	0.25%	2.0	

Table E-24: Rockwood (Pit 58-8) 3/4"-1 1/4" (cont)

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
1	1	46	1150	90	2680	201	9/12/95	9/14/95	10	2679	0	202	0	0.04%	0.5	91
								9/15/95	20	2676	1.6	202	2	0.09%	1.0	
								9/18/95	30	2674	1.9	202	3	0.15%	1.2	
								9/20/95	40	2672	3.1	203	5	0.18%	2.2	
								9/21/95	50	2671	3.1	204	5	0.22%	2.7	
1	1	47	1150	90	2871	200	9/12/95	9/14/95	10	2868	0.6	200	1	0.08%	0.3	500+
								9/15/95	20	2866	0.6	200	1	0.15%	0.3	
								9/18/95	30	2865	0.6	200	1	0.19%	0.3	
								9/20/95	40	2865	0.6	200	1	0.19%	0.3	
								9/21/95	50	2863	0.6	200	1	0.26%	0.3	
1	1	48	1150	90	2569	200	9/13/95	9/14/95	10	2566	0	200	0	0.12%	0.0	167
								9/18/95	20	2564	0.3	200	1	0.18%	0.3	
								9/19/95	30	2564	0.3	200	1	0.18%	0.3	
								9/20/95	40	2562	0.3	200	1	0.26%	0.3	
								9/21/95	50	2560	1.1	202	2	0.31%	1.5	
1	1	49	1150	90	2781	200	9/13/95	9/14/95	10	2779	0	200	0	0.07%	0.0	500
								9/18/95	20	2777	0.4	200	1	0.13%	0.3	
								9/19/95	30	2775	0.4	200	1	0.20%	0.3	
								9/20/95	40	2774	0.4	200	1	0.24%	0.3	
								9/21/95	50	2771	0.8	200	2	0.33%	0.5	
1	1	50	1150	85	2814	200	9/13/95	9/14/95	10	2674	0.8	210	3	0.04%	0.7	150
								9/18/95	20	2672	0.8	210	3	0.12%	0.7	
								9/19/95	30	2670	1.6	211	5	0.16%	1.7	
								9/20/95	40	2669	1.6	211	5	0.20%	1.7	
								9/21/95	50	2668	1.6	211	5	0.24%	1.7	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.039	N/A	0.039	N/A	Durability Factor	38	N/A	37	N/A

Table E-25: Dolomite and Sandstone 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
1	1	1	1150	90	2893	176	5/8/95	5/9/95	10	2891	0	176	0	0.07%	0.0	52
								5/17/95	20	2887	0	178	0	0.21%	1.1	
								5/18/95	30	2882	0.8	180	2	0.35%	2.8	
								5/22/95	40	2875	3.11	181	5	0.51%	4.3	
								5/23/95	50	2872	3.11	182	5	0.62%	4.8	
1	1	2	1150	90	2910	170	5/8/95	5/17/95	10	2909	0	170	0	0.03%	0.0	85
								5/18/95	20	2906	0	170	0	0.14%	0.0	
								5/22/95	30	2900	1.38	171	2	0.30%	1.2	
								5/23/95	40	2897	1.57	172	3	0.39%	2.1	
								5/24/95	50	2892	2.63	173	4	0.53%	2.9	
1	1	3	1150	90	2878	180	7/14/95	7/20/95	10	2872	0	181	0	0.21%	0.6	113
								7/21/95	20	2866	0.95	182	2	0.38%	1.7	
								7/22/95	30	2860	1.18	182	3	0.58%	1.9	
								7/25/95	40	2855	1.18	182	3	0.76%	1.9	
								7/26/95	50	2849	1.48	182	4	0.96%	2.2	
1	1	4	1150	90	2993	180	UT	7/20/95	10	2989	0	181	0	0.13%	0.6	225
								7/22/95	20	2986	0	181	0	0.23%	0.6	
								7/24/95	30	2982	0.99	181	2	0.33%	1.1	
								7/25/95	40	2978	0.99	181	2	0.47%	1.1	
								7/26/95	50	2976	0.99	181	2	0.53%	1.1	
1	1	5	1150	90	2803	180	UT	6/21/95	10	2798	0.45	181	1	0.16%	0.8	150
								6/22/95	20	2795	0.45	181	1	0.27%	0.8	
								6/23/95	30	2790	1.05	181	4	0.43%	1.7	
								6/27/95	40	2787	1.05	181	4	0.53%	1.7	
								6/28/95	50	2785	1.05	181	4	0.60%	1.7	
1	1	6	1150	90	2948	180	UT	6/21/95	10	2943	1.27	180	2	0.13%	0.6	450
								6/22/95	20	2941	1.27	180	2	0.19%	0.6	
								6/23/95	30	2938	1.27	180	2	0.30%	0.6	
								6/27/95	40	2934	1.27	180	2	0.43%	0.6	
								6/28/95	50	2932	1.27	180	2	0.50%	0.6	

Table E-26: Dolomite and Siltstone 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
1	1	1	1150	90	2839	175	5/9/95	5/23/95	10	2825	7.2	177	24	0.24%	8.0	6
								5/24/95	20	2814	12.62	182	38	0.44%	14.9	
								5/26/95	30	2805	16.59	181	47	0.61%	16.9	
								5/30/95	40	2794	22.01	183	63	0.81%	22.6	
								5/21/95	50	2788	24.62	188	68	0.93%	26.9	
1	1	2	1150	90	2604	175	5/9/95	5/23/95	10	2591	5.71	181	22	0.28%	9.7	5
								5/24/95	20	2574	15.9	182	45	0.54%	16.9	
								5/26/95	30	2565	20.22	183	57	0.72%	20.9	
								5/30/95	40	2557	23.45	186	65	0.90%	24.9	
								5/21/95	50	2549	28.56	184	77	1.02%	27.1	
1	1	5	1150	90	2896	172	UT	6/14/95	10	2882	3.82	178	17	0.35%	8.4	6
								6/15/95	20	2873	6.84	178	24	0.56%	10.5	
								6/16/95	30	2870	7.82	178	27	0.63%	11.3	
								6/17/95	40	2865	8.32	178	29	0.78%	11.9	
								6/20/95	50	2862	10.57	180	34	0.81%	14.5	
1	1	6	1150	90	2889	172	UT	6/14/95	10	2874	0.4	175	1	0.51%	2.0	25
								6/15/95	20	2871	2.14	175	6	0.55%	3.5	
								6/16/95	30	2863	4.92	176	14	0.73%	6.4	
								6/17/95	40	2855	8.5	177	23	0.88%	9.6	
								6/20/95	50	2850	10.37	179	29	0.99%	12.5	

Table E-27: Dolomite and Shale 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results										
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
1	1	1	1150	90	3051	180	5/31/95	6/1/95	10	3045	3.5	181	9	0.08%	3.1	15
								6/7/95	20	3042	4.88	186	13	0.14%	6.9	
								6/8/95	30	3035	8.1	189	21	0.26%	10.8	
								6/13/95	40	3032	10.37	188	27	0.28%	11.9	
								6/14/95	50	3030	11.59	191	31	0.31%	14.7	
1	1	2	1150	90	2997	180	5/31/95	6/2/95	10	2994	1.28	187	5	0.06%	5.3	9
								6/7/95	20	2993	2.12	188	6	0.06%	6.1	
								6/8/95	30	2989	3.4	188	12	0.15%	7.8	
								6/13/95	40	2986	5.4	193	20	0.19%	12.8	
								6/14/95	50	2982	8.17	193	27	0.23%	14.7	
1	1	5	1150	90	2786	176	UT	6/15/95	10	2781	3.04	180	7	0.07%	4.3	13
								6/16/95	20	2778	3.91	183	9	0.15%	6.5	
								6/17/95	30	2778	4.11	189	10	0.14%	10.2	
								6/20/95	40	2774	6.26	190	15	0.21%	12.2	
								6/21/95	50	2770	9.98	196	23	0.22%	17.9	
1	1	6	1150	90	2728	176	UT	6/15/95	10	2721	4.44	182	14	0.09%	7.4	7
								6/16/95	20	2718	5.75	183	19	0.16%	9.4	
								6/17/95	30	2712	8.52	188	26	0.27%	14.2	
								6/20/95	40	2704	14.7	188	39	0.34%	17.9	
								6/21/95	50	2697	17.19	188	46	0.51%	19.9	

Table E-28: Dolomite and Clayironstone 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
1	1	1	1150	90	3063	176	6/8/95	6/13/95	10	3059	5.09	180	12	-0.04%	5.7	9
								6/14/95	20	3046	13.27	180	24	0.12%	9.1	
								6/15/95	30	3037	17.2	186	35	0.29%	15.6	
								6/16/95	40	3031	18.94	189	38	0.43%	18.2	
								6/20/95	50	3028	20.61	188	41	0.47%	18.5	
1	1	2	1150	90	2872	176	6/8/95	6/13/95	10	2867	3.4	182	8	0.06%	5.7	9
								6/14/95	20	2866	4.12	184	10	0.07%	7.4	
								6/15/95	30	2863	5.56	185	13	0.12%	8.8	
								6/16/95	40	2858	7.72	188	18	0.22%	11.9	
								6/20/95	50	2852	10.78	188	25	0.32%	13.9	
1	1	5	1150	90	3081	180	UT	6/20/95	10	3075	2.69	182	6	0.11%	2.8	14
								6/21/95	20	3062	8.3	188	16	0.35%	8.9	
								6/22/95	30	3047	17.77	191	35	0.53%	15.8	
								6/23/95	40	3036	24.78	194	49	0.66%	21.4	
								6/26/95	50	3034	26.04	195	51	0.68%	22.5	
1	1	6	1150	90	2847	180	UT	6/20/95	10	2841	2.26	186	9	0.13%	5.8	9
								6/21/95	20	2834	5.37	187	16	0.27%	8.3	
								6/22/95	30	2830	7.09	192	20	0.35%	12.2	
								6/23/95	40	2822	11.68	193	29	0.47%	15.3	
								6/26/95	50	2817	16.15	196	38	0.49%	19.4	

Table E-29: Dolomite and Chert 3/4"-1"

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
1	1	1	1150	90	2885	180	6/8/95	6/13/95	10	2884	0	180	0	0.03%	0.0	500+
								6/14/95	20	2884	0	180	0	0.03%	0.0	
								6/15/95	30	2883	0	180	0	0.07%	0.0	
								6/16/95	40	2882	0	180	0	0.10%	0.0	
								6/17/95	50	2881	0	180	0	0.14%	0.0	
1	1	2	1150	90	2873	180	6/8/95	6/13/95	10	2872	0	180	0	0.03%	0.0	500+
								6/14/95	20	2872	0	180	0	0.03%	0.0	
								6/15/95	30	2870	0	180	0	0.10%	0.0	
								6/16/95	40	2870	0	180	0	0.10%	0.0	
								6/17/95	50	2869	0	180	0	0.14%	0.0	
1	1	5	1150	90	2966	180	UT	6/13/95	10	2965	0	180	0	0.03%	0.0	500+
								6/14/95	20	2964	0	180	0	0.07%	0.0	
								6/15/95	30	2963	0	180	0	0.10%	0.0	
								6/16/95	40	2963	0	180	0	0.10%	0.0	
								6/17/95	50	2962	0	180	0	0.13%	0.0	
1	1	6	1150	90	2826	180	UT	6/13/95	10	2824	0	180	0	0.07%	0.0	500+
								6/14/95	20	2824	0	180	0	0.07%	0.0	
								6/15/95	30	2823	0	180	0	0.11%	0.0	
								6/16/95	40	2822	0	180	0	0.14%	0.0	
								6/17/95	50	2820	1.33	180	1	0.17%	0.3	
2	4	3	1150	150	3080.1	180	N/A	7/6/95	10	3077.8	0.6	181	1	0.06%	0.8	113
								7/7/95	20	3075.5	0.6	181	1	0.13%	0.8	
								7/10/95	30	3074.9	1.7	181	2	0.11%	1.1	
								7/11/95	40	3069.5	1.92	181	3	0.28%	1.4	
								7/13/95	50	3068.6	2.68	181	6	0.29%	2.2	
2	3	4	1150	150	2984.6	180	N/A	7/5/95	10	2981.2	0	182	0	0.11%	1.1	100
								7/7/95	20	2977.5	1.9	182	5	0.17%	2.5	
								7/11/95	30	2971.4	1.9	182	5	0.38%	2.5	
								7/12/95	40	2971	1.9	182	5	0.39%	2.5	
								7/13/95	50	2969.6	1.9	182	5	0.44%	2.5	

Appendix F

Supplementary Data Summary Tables

Note: Data presented in this appendix were used in the preliminary stages of the study to determine appropriate release rates, sample sizes and to calibrate equipment. The were *not* used in any of the analysis described in the report because they do not represent the results of the "standard" test procedure. These data should be used for analysis *only* with extreme caution and consideration of the conditions of each specific test.

Table F-1. Bundy Hill (30-35) 12.5 - 19 mm

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	5	1	1050	120	3043.9	450	2/2/95	2/6/95	10	3037.5	0	450	0	0.21%	0.0	500+
								2/20/95	20	3038.3	0	450	0	0.18%	0.0	
								2/21/95	30	3037.7	0	451	0	0.20%	0.2	
								2/23/95	40	3037.5	0	451	0	0.21%	0.2	
								2/28/95	50	3034.1	1.5	447	2	0.27%	-0.4	
2	3	1	1050	120	3451.7	537	3/1/95	3/1/95	10	3448.2	2.5	535	2	0.03%	-0.2	192
								3/2/95	20	3445	4.54	532	4	0.06%	-0.6	
								3/3/95	30	3439.7	6.86	532	9	0.15%	-0.1	
								3/4/95	40	3428.1	10.94	535	15	0.37%	1.0	
								3/5/95	50	3424.7	11.18	536	16	0.46%	1.3	
2	3	2	1050	120	3487.9	500	3/1/95	3/1/95	10	3476.7	1.55	499	6	0.28%	0.4	100
								3/2/95	20	3479.1	2.44	500	8	0.18%	0.8	
								3/3/95	30	3474.2	5.1	501	13	0.25%	1.5	
								3/4/95	40	3469.4	7.7	489	19	0.31%	-0.3	
								3/5/95	50	3464.2	9.9	501	23	0.40%	2.5	
2	6	S1	1050	120	3725.1	588	3/2/95	3/7/95	10	3717.6	6.5	584	5	0.03%	-0.3	380
								3/8/95	20	3716.5	6.8	584	6	0.05%	-0.2	
								3/11/95	30	3715.2	7.3	585	7	0.07%	0.1	
								3/13/95	40	3710.9	9.1	584	8	0.14%	0.0	
								3/14/95	50	3708.1	9.5	585	9	0.20%	0.3	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.029	0.049	0.059	0.065

	MDot-file	MDot	U of MI	U of MN
Durability Factor	47	30	24	21

Table F-2. Bundy Hill (30-35) 19 - 25 mm

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results										
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	5	1	1050	120	3337.5	200	2/2/95	2/6/95	10	3333.7	0	204	0	0.11%	2.0	67
								2/10/95	20	3332.3	0	204	0	0.16%	2.0	
								2/22/95	30	3331.6	0.2	206	1	0.17%	3.3	
								N/A	40	3328.2	1.7	205	5	0.23%	3.8	
								N/A	50	3327.6	1.7	205	5	0.25%	3.8	
2	5	2	1050	120	3356.6	200	2/2/95	2/2/95	10	3352	0	200	0	0.14%	0.0	40
								2/10/95	20	3350.1	0.3	201	1	0.18%	0.8	
								N/A	30	3345.9	3.23	205	7	0.22%	4.3	
								N/A	40	3344.5	3.44	206	8	0.26%	5.0	
								N/A	50	3340.5	5.18	207	14	0.33%	7.0	
2	3	1	1050	120	3805.3	231	2/17/95	2/18/95	10	3785.6	0.09	233	1	0.52%	1.1	31
								2/22/95	20	3781.9	1.73	236	5	0.57%	3.2	
								2/23/95	30	3780.7	1.98	238	6	0.59%	4.3	
								2/24/95	40	3764.1	9.16	243	23	0.84%	10.2	
								2/25/95	50	3758.6	15.02	240	32	0.83%	10.8	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.029	0.049	0.059	0.065	Durability Factor	47	30	24	21

Table F-3. Drummond (17-66) 12.5 - 19 mm

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	6	1	1050	120	3206.9	580	2/9/95	2/9/95	10	3197.8	0	580	0	0.28%	0.0	500+
								2/16/95	20	3193.6	2.2	579	2	0.35%	0.0	
								2/20/95	30	3192.1	2.2	580	2	0.39%	0.2	
								2/25/95	40	3190.7	2.7	580	3	0.42%	0.3	
								2/28/95	50	3188	3.9	579	4	0.47%	0.2	
2	6	2	1050	120	3183.8	600	2/9/95	2/9/95	10	3170.6	2	599	1	0.35%	-0.1	500+
								2/10/95	20	3169.2	2	599	1	0.40%	-0.1	
								2/16/95	30	3167	2	599	1	0.46%	-0.1	
								2/20/95	40	3164.4	3.4	599	3	0.50%	0.1	
								2/25/95	50	3163.2	3.4	599	3	0.54%	0.1	
2	3	1	1050	120	3405.2	650	3/8/95	3/8/95	10	3401	2.46	648	2	0.05%	-0.2	500+
								3/9/95	20	3397.5	4.27	647	3	0.10%	-0.2	
								3/20/95	30	3395.6	4.27	647	3	0.16%	-0.2	
								3/21/95	40	3392.9	5.96	646	4	0.19%	-0.3	
								3/22/95	50	3386.3	5.97	646	5	0.38%	-0.2	
2	5	1	1050	120	3439.7	625	3/3/95	3/6/95	10	3430.6	1.12	623	1	0.23%	-0.2	500+
								3/7/95	20	3428.1	1.83	623	3	0.28%	-0.1	
								3/8/95	30	3426.5	1.83	624	3	0.33%	0.1	
								3/14/95	40	3424	2.84	625	5	0.37%	0.4	
								3/16/95	50	3420.5	4.88	624	6	0.42%	0.3	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.005	0.001	0.001	0.002	Durability Factor	89	98	98	95

Table F-4. Drummond (17-66) 19 - 25 mm

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	6	1	1050	120	3094.8	249	2/3/95	2/9/95	10	3088.9	0	249	0	0.19%	0.0	500+
								2/14/95	20	3087.8	0	249	0	0.23%	0.0	
								2/16/95	30	3086.2	0	249	0	0.28%	0.0	
								2/20/95	40	3084.4	0	249	0	0.34%	0.0	
								2/25/95	50	3083.2	0.74	249	1	0.35%	0.2	
2	6	2	1050	120	3261.3	261	2/3/95	2/9/95	10	3258.9	0	261	0	0.07%	0.0	261
								2/14/95	20	3256.6	0.4	261	1	0.13%	0.2	
								2/16/95	30	3254.9	0.4	263	1	0.18%	1.0	
								2/20/95	40	3253.1	0.4	263	1	0.24%	1.0	
								2/25/95	50	3252.2	0.4	263	1	0.27%	1.0	
2	3	1	1050	120	3356	287	3/8/95	3/8/95	10	3354	0.39	289	1	0.05%	0.9	500+
								3/9/95	20	3352.9	0.39	287	1	0.08%	0.2	
								3/10/95	30	3352.4	0.39	287	1	0.10%	0.2	
								3/21/95	40	3351.4	0.39	287	1	0.13%	0.2	
								3/22/95	50	3350.6	0.39	287	1	0.15%	0.2	
2	5	1	1050	120	3445.6	284	3/3/95	3/6/95	10	3430.6	0.27	283	1	0.43%	-0.2	473
								3/7/95	20	3428.7	0.42	283	2	0.48%	0.0	
								3/8/95	30	3426.8	0.76	283	4	0.52%	0.4	
								3/14/95	40	3425.9	0.76	283	4	0.55%	0.4	
								3/20/95	50	3423.4	1.16	283	5	0.61%	0.5	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.005	0.001	0.001	0.002

	MDot-file	MDot	U of MI	U of MN
Durability Factor	89	98	98	95

Table F-5. Marblehead (93-1) 12.5 - 19 mm

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	5	1	1050	120	2636.2	450	1/31/95	1/31/95	10	2607.9	0.2	450	0	1.07%	0.0	450
								2/2/95	20	2623.7	0.6	451	3	0.45%	0.6	
								N/A	30	2622	0.6	451	3	0.52%	0.6	
								N/A	40	2620.1	0.6	451	3	0.59%	0.6	
								N/A	50	2618.8	0.6	451	3	0.64%	0.6	
2	3	1	1050	120	3376.9	579	2/1/95	2/2/95	10	3363.8	0.79	579	3	0.36%	0.3	414
								2/3/95	20	3364	2.4	578	4	0.31%	0.2	
								2/4/95	30	3353	2.4	578	4	0.64%	0.2	
								3/13/95	40	3350.3	2.4	580	4	0.72%	0.5	
								2/15/95	50	3348	2.58	580	5	0.78%	0.6	
2	3	2	1050	120	3319.2	585	2/1/95	2/1/95	10	3313.2	0.96	587	1	0.15%	0.4	488
								2/2/95	20	3304	0.96	587	1	0.43%	0.4	
								2/8/95	30	3302.4	0.96	587	1	0.48%	0.4	
								2/10/95	40	3300.9	1.6	587	2	0.50%	0.5	
								2/12/95	50	3291.8	1.6	587	2	0.78%	0.5	
2	5	1	1150	90	3184.8	584	3/30/95	4/21/95	10	3180.3	0	584	0	0.14%	0.0	500+
								4/24/95	20	3182	0	585	0	0.09%	0.2	
								4/25/95	30	3180.2	0	585	0	0.14%	0.2	
								4/28/95	40	3178.4	0	584	0	0.20%	0.0	
								5/4/95	50	3176.9	0	585	0	0.25%	0.2	
2	6	1	1150	90	3096.4	597	5/10/95	5/28/95	10	3088.4	0	597	0	0.26%	0.0	500+
								6/11/95	20	3085.4	0.44	597	1	0.34%	0.1	
								6/12/95	30	3082.6	0.44	597	1	0.45%	0.1	
								6/13/95	40	3081.4	0.44	597	1	0.47%	0.1	
								6/14/95	50	3079.5	0.44	597	1	0.53%	0.1	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.075	0.059	0.057	0.067	Durability Factor	17	24	25	20

Table F-6. Marblehead (93-1) 19 - 25 mm

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results										
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	5	1	1050	120	2842.5	225	1/31/95	1/31/95	10	2829.8	0	226	0	0.45%	0.4	188
								2/1/95	20	2827.2	0	226	0	0.54%	0.4	
								N/A	30	2826.2	0	227	0	0.57%	0.9	
								N/A	40	2824	0	228	0	0.65%	1.3	
								2/23/95	50	2822.7	0	228	0	0.70%	1.3	
2	5	2	1050	120	2791.7	225	1/31/95	1/31/95	10	2781.1	0	226	0	0.38%	0.4	375
								2/2/95	20	2779	0	227	0	0.45%	0.9	
								N/A	30	2777.4	0.9	226	1	0.48%	0.7	
								N/A	40	2775.4	0.9	226	1	0.55%	0.7	
								2/23/95	50	2774.5	0.9	226	1	0.58%	0.7	
2	3	1	1050	120	3315.5	259	2/17/95	2/19/95	10	3314.5	0	259	0	0.03%	0.0	216
								2/22/95	20	3309	0.68	259	1	0.18%	0.2	
								2/24/95	30	3305.8	0.68	259	1	0.27%	0.2	
								2/25/95	40	3305.1	1.05	260	2	0.28%	0.8	
								2/26/95	50	3303.2	1.05	261	2	0.34%	1.2	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.075	0.059	0.057	0.067	Durability Factor	17	24	25	20

Table F-7. Rockwood (58-8) 12.5 - 19 mm

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results										
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	5	1	1050	120	2525.3	450	1/10/95	1/10/95	10	2519.4	3	445	6	0.11%	-0.4	150
								1/17/95	20	2521.3	3.9	446	8	0.00%	0.0	
								1/19/95	30	2513	7.2	447	17	0.20%	1.2	
								1/25/95	40	2510.3	7.9	446	19	0.28%	1.2	
								2/10/95	50	2508.9	7.9	448	19	0.34%	1.7	
2	5	2	1050	120	2417.4	450	1/10/95	1/10/95	10	2414.4	1	447	2	0.08%	-0.4	500+
								1/17/95	20	2415.1	2.6	447	3	-0.01%	-0.3	
								1/21/95	30	2410.2	4.3	449	7	0.12%	0.6	
								1/25/95	40	2408.5	4.3	447	7	0.19%	0.1	
								1/20/95	50	2406	5.1	447	8	0.26%	0.2	
2	3	1	1050	120	2472	400	1/11/95	1/11/95	10	2483.9	3.39	428	8	-0.62%	8.0	6
								1/13/95	20	2456.6	5.38	446	11	0.41%	12.9	
								1/17/95	30	2455.6	5.55	446	12	0.44%	13.0	
								1/26/95	40	2451.2	6.72	446	13	0.57%	13.1	
								1/28/95	50	2448.1	9.45	446	18	0.58%	13.8	
2	6	1	1050	120	2990.7	506	3/1/95	3/1/95	10	2986.3	0	506	0	0.15%	0.0	281
								3/10/95	20	2982.8	0.6	507	2	0.24%	0.4	
								3/11/95	30	2977.8	3.3	506	4	0.32%	0.4	
								3/13/95	40	2972	4.7	506	7	0.47%	0.7	
								3/14/95	50	2967.9	5.1	506	9	0.59%	0.9	
2	6	2	1050	120	2940.2	564	3/1/95	3/2/95	10	2933.5	2.2	566	4	0.15%	0.7	113
								3/3/95	20	2930.5	2.6	566	6	0.24%	0.9	
								3/7/95	30	2922.8	6.2	563	13	0.38%	1.0	
								3/11/95	40	2919.3	6.2	565	13	0.50%	1.3	
								3/13/95	50	2913.3	8.9	567	19	0.61%	2.2	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.039	N/A	0.039	N/A
Durability Factor	38	N/A	37	N/A

Table F-8. Rockwood (58-8) 19 - 25 mm

HYDRAULIC FRACTURE DATA

Sample Information			Testing Conditions				Test Results									
Test Apparatus	Test Operator	Sample Number	Chamber Pressure (psi)	Solenoid Pressure (psi)	Initial Mass (g)	Initial Count	Date Treated	Testing Dates	Cycles	Mass +9.5 mm (g)	Mass 9.5 to 4.75 mm (g)	Count +9.5 mm	Count 9.5 to 4.75 mm	Mass Loss	Percent Fractures	HFI
2	3	1	1050	120	3159	200	1/10/95	1/10/95	10	3157.9	0.1	243	2	0.03%	22.0	2
								1/13/95	20	3137.3	0.8	254	6	0.66%	28.5	
								1/17/95	30	3126.4	6.03	258	16	0.84%	33.0	
								1/26/95	40	3117.4	7.33	258	19	1.09%	33.8	
								1/28/95	50	3088.6	12.05	260	29	1.85%	37.3	
2	3	2	1050	120	3116	240	1/10/95	1/10/95	10	3110.8	0	240	0	0.16%	0.0	49
								1/13/95	20	3108.3	0	240	0	0.24%	0.0	
								1/17/95	30	3107.9	0.9	240	1	0.22%	0.2	
								1/26/95	40	3110.5	3.65	245	5	0.05%	3.1	
								1/28/95	50	3108.1	5.3	248	9	0.07%	5.2	
2	5	1	1050	120	2710	200	1/10/95	1/10/95	10	2709	0.2	202	1	0.04%	1.3	59
								1/17/95	20	2708.9	0.8	202	3	0.03%	1.8	
								1/19/95	30	2706.6	1.4	204	8	0.09%	4.0	
								1/25/95	40	2701.5	3.8	203	11	0.19%	4.3	
								1/30/95	50	2688.6	5.5	202	13	0.60%	4.3	
2	6	1	1050	120	2920	222	2/28/95	3/7/95	10	2916	0.9	223	3	0.11%	1.1	79
								3/8/95	20	2912.2	1.1	223	4	0.23%	1.4	
								3/9/95	30	2909.1	1.6	224	6	0.32%	2.3	
								3/10/95	40	2905.2	2.7	225	8	0.42%	3.2	
								3/13/95	50	2904.3	2.7	225	8	0.45%	3.2	

FREEZE-THAW DATA

	MDot-file	MDot	U of MI	U of MN		MDot-file	MDot	U of MI	U of MN
% Dilation/100 Cycles	0.039	N/A	0.039	N/A	Durability Factor	38	N/A	37	N/A