Florida Power CORPORATION

DESIGN ANALYSIS/CALCULATION

Crystal River Unit 3

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DOCUMENT IDENTIFICATION NO.	REVISION
S-00-0047	0

Title: "As-Built Concrete Strength for Class I Structures"

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I. Purpose

The purpose of this calculation is to determine the in-place strength of concrete for use in evaluating concrete anchor spacing issues. This calculation applies to major Class I structures with the exception of the Emergency Feedwater Tank Enclosure and Diesel Driven Emergency Feedwater Pump Enclosure.

II. Results / Conclusions

A statistical evaluation of concrete test cylinder results for Class 3000 concrete was performed in accordance with current American Concrete Institute codes and standards to determine the as-placed concrete compressive strength. Samples of test cylinder data were evaluated to determine the concrete strength gain due to short term curing/aging. The CR3 test data was compared to long-term aging research to determine the magnitude of strength gain due to aging at CR3. All of the previous factors were combined to determine the in-place concrete strength at CR3.

The in-place compressive strength for concrete in Class I structures is as shown below. Exception areas for Class 3000 concrete are shown in Attachment J. There are several areas where Class 3000 concrete was specified on the structural drawings, but Class 5000 concrete was actually placed. Those areas can be identified through review of Attachment B. The Class 5000 in-place compressive strength value can be used in those areas for evaluation of local effects, such as concrete anchor spacing violations.

Class 3000 (other than in exception areas)	5460 psi
Class 3000 in exception areas	4860 psi
Class 5000	6720 psi

III. Design Input

Concrete Pour records are located in the Construction Microfiche files starting with 1P02032 through 1P10096 and continuing at 1C01001 through 1C10033A.

No active CR3 plant drawings relating the Pour designations used in the construction records to specific plant locations were located. Many of the Pours have sketches in the microfiche records, and there are references to "CR3-S" series drawings that were not retained after construction.

Design Strength of Concrete (Refs. 1, 2, & 3)

- The specified 28-day design strength for Class I Structures is as follows:

Containment & Containment Interior Structures	5000 psi
except Floors at El 119 & 160 and Elevator	3000 psi
All other Class I Structures	3000 psi

- Class I Structures are as defined in the EDBDs (Refs. 1, 2,& 3)
- Type II cement was specified for all structural concrete (Ref. 4)
- Concrete testing was performed in accordance with ACI 301-66 (Ref. 4, SP-5569).
- Concrete design was performed in accordance with ACI 318-63 (Refs. 1, 2, & 3)

IV. Assumptions

None requiring later verification

The average compressive strength and standard deviation statistics calculated were based on the results of individual cylinder break results, rather than the average of two cylinder break tests. This was done for convenience because the construction data for CR3 had a few pours with only one valid cylinder break. The effect on average strength in insignificant for populations of sufficient size. The effect of this methodology on the standard deviation of the population being evaluated is conservative, because it always results in a larger value for the standard deviation. However, for large sample sizes the difference in standard deviation is small and does not effect the results of this evaluation.

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V. References

1. "Design Basis Document for the Containment", Rev. 2, Tab 1/1
2. "Design Basis Document for the Containment Interior Structures", Rev. 1, Tab 1/2
3. "Design Basis Document for Major Class I Structures", Rev. 1, Tab 1/3
4. SP-5569 through Addendum D, "Specification for Furnishing and Delivering of Structural Concrete"
5. ACI 214-77, "Recommended Practice for Evaluation of Strength Test Results of Concrete", Reapproved 1989
6. ACI 214.3R-88, "Simplified Version of the Recommended Practice for Evaluation of Strength Test Results of Concrete"
7. ACI-225R-91, "Guide to the Selection and Use of Hydraulic Cements"
8. ACI 301-89, "Specifications for Structural Concrete for Buildings"
9. ACI 318-89,"Building Code Requirements for Reinforced Concrete", Revised 1992
10. ACI 349-90, "Code Requirements for Nuclear Safety Related Concrete Structures"
11. ACI 363R-92, "State-of-the-Art Report on High-Strength Concrete"
12. Waddell, Joseph J.(Editor), "Concrete Construction Handbook", McGraw-Hill Book Co., 1968

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VI. Detailed Calculations

Background

The compressive strength of concrete increases with age if moisture is present. Strength increases have been documented for aging up to 50 years, generally following a logarithmic curve (Ref. 12). At early ages, higher-strength concrete shows a higher rate of strength gain (in terms of absolute strength) as compared to lower-strength concrete. However, after approximately 95 days the differences in normalized strength gain are not significant (Ref. 11). When normalized to 90-day compressive strength, typical concrete made from Type II cement shows a strength gain of approximately 25% after 5 years (Ref. 7, Fig. 6.1).

Variations in strength test results are due to differences in the strength-producing properties of the concrete mixture and ingredients, and apparent differences due to variations inherent in testing. It is well established that concrete strength is governed to a large extent by the water-cement ratio. The results of concrete cylinder tests for a specific mix design produced over time with good quality control are expected to fall into a pattern similar to the normal frequency distribution curve. (Ref. 5)

The required average compressive strength f'_{cr} to be used for selection of a concrete mix is the larger of the following (ACI 318-89 5.3.2.1 & ACI 349-90 4.3.2.1):

$$f'_{cr} = f'_c + 1.34\ s$$

or

$$f'_{cr} = f'_c + 2.33\ s - 500$$

where f'_c is the specified design compressive strength, and s is the standard deviation of the compressive strength test results. These equations provide a probability of about 1% that the averages of 3 consecutive strength test results will be below the specified f'_c, and a similar probability that any individual test will be more than 500 psi below the specified compressive strength. The standard deviation s is to be determined from a minimum of 30 tests. However, 100 tests are recommended. Each test is the average of at least 2 cylinders made from the same batch of concrete, cured under the same conditions, and tested at the same age (Ref. 6).

The strength level of an individual class of concrete is considered satisfactory if both of the following requirements are met (ACI 318-89 5.6.2.3 & ACI 349-90 4.7.2.3):

(a) average of all sets of three consecutive strength tests $\geq f'_c$

and

(b) no individual strength test (average of two cylinders) $< (f'_c - 500\text{ psi})$

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Methodology

Structural concrete for Class I structures at CR3 is either Class 3000 or Class 5000 (the lone exception being the RB Dome repair which utilized Class 6000 concrete). Although several different mixes were used for the Class 5000 concrete, the materials used were the same as the Class 3000 concrete. Type II cement was used to minimize heat development and the subsequent volume changes and cracking during hydration of the cement. All of the structural concrete used the same admixtures (Darex and Daratard). The major difference between the Class 3000 and Class 5000 concrete mixes are the water-cement ratio.

The concrete mixes most often used for Class I concrete at CR3 are as follows:

Mix	Class	Comments
658550-2	6000	RB Dome repair only
727550-2	5000	
736441	5000	Primarily used in Ring Girder
DM-5	5000	
DM-7	5000	Primarily used for repairs
T-21510	3000	

The three mixes used for the bulk of the large structural pours are T-21510, DM-5, and 727550-2. It appears that DM-5 was the Class 5000 concrete mix early in the job, and 727550-2 replaced DM-5 for later pours. Mix 727550-2 had a higher cement factor.

As would be expected for a concrete construction job as large as CR3, all of the mixes underwent small modifications during the project. Cursory review indicates that the mix modifications were to the cement factor (bag/cu yd), and that water-cement ratios were held constant. Since the water-cement ratio is the single most important factor influencing concrete strength, any minor effects on compressive strength and the rate of strength gain due to the mix modifications are not considered in this calculation. A mix designation as used in this calculation includes all modifications of the mix.

This calculation will evaluate two different aspects of concrete strength at CR3:

1. Long-term strength gain for Class 3000 and Class 5000 concrete
   a. 28 to 90-day strength gain
   b. Post 90-day strength gain
   c. Discussion of conservatism
2. As-placed concrete strength for Class 3000 concrete

The specified compressive strengths for concrete at CR3 were 28-day strengths. For the purposes of this calculation, long-term strength gains are considered as those occurring after 28 days. The strength gain over a time increment will be determined as ratio f_{cT1} / f_{cT0}. The use of the ratio essentially normalizes the data, and breaks the strength vs. time curve into linear segments.

Ample data exists for Class 5000 concrete to determine the 28-day and 90-day average compressive strengths from statistically significant samples. Class 3000 concrete has only limited 90-day test data, which will be evaluated to determine its validity. Strength gains from 7 to 28 to 90 days for the limited data set will be compared to 7 to 28 day strength gains for a statistically significant sample of Class 3000 cylinder test data.

There is no test data for CR3 concrete past 90 days. Strength gains past 90 days will be conservatively estimated by comparison of CR3 concrete to research presented in the literature.

Concrete mixes are conservatively designed to exceed the compressive strength required, due to the inherent strength variations of the as-placed mixture caused by a many conditions that vary in the field. The ACI codes recognize the potential for strength variations, and specify the margin required for a concrete mix design. The codes allow for a statistically small amount of concrete that may be less than the specified design strength. If good quality control is used during construction, the concrete placed may be significantly stronger than required by the design specifications.

For calculations where concrete strength is a critical factor, such as for anchor spacing evaluations, there is a large benefit to taking advantage of higher concrete strengths. Therefore, the 28-day test data for Class 3000 concrete placed for the Class I structures of interest will be reviewed to determine the strength of concrete that was actually placed. A statistical evaluation of the data will be performed and each set of data will be checked against the ACI compressive strength acceptability criteria previously discussed.

Sufficient data also exists to determine the as-placed compressive strength for Class 5000 concrete. However, due to the effort required to retrieve the test data and the already higher specified strength, the evaluation is not warranted for Class 5000 concrete.

In order to evaluate the concrete used in Class I structures at CR3, the concrete pour records were reviewed. The structures of interest are primarily the RB, AB, CC, IB, and DGB, since those buildings are where the vast majority of safety related concrete anchorages are located. Concrete pours for Berm Protection (wave steps) and Hurricane Protection walls were included in the review only to the extent that test data from those pours was relevant to the structures of interest. Also note that only the east side of the Intake Structure is considered Class I.

The concrete pours for the buildings of interest were generally numbered in sequential order, with a suffix indicating the building or structure. The pour records reviewed generally have a pour slip with data about the pour, truck slips and QC reports, usually a sketch showing the specific pour location, and test data for test cylinders associated with the pour.

A listing of the concrete pours reviewed is shown in Attachment A. The location description and elevations shown for the top of the pour should be considered reference only; for specific details the pour records should be consulted.

Attachment B shows concrete pours generally grouped by building and location. Again, the descriptions used for the list are not precise and the construction records should be consulted for specific details.

Long-term Strength Gain

A. 28 to 90-Day Strength Gain

The specified concrete strengths for concrete at CR3 were 28-day strengths. Class 5000 concrete generally had test cylinders broken at 7, 28, and 90 days. The Class 3000 concrete generally had only 7 and 28 day test cylinders. However, two sets of test cylinders for Mix T-21510 (Pours 28-DHP and 29-DHP) had 90 day tests.

Test cylinder data was retrieved for approximately 100 sets of cylinders each for Mixes T-21510, DM-5, and 727550-2. The sample size of at least 100 tests is per ACI recommendations for determination of compressive strength statistics. The average break strengths for the test cylinders were analyzed to determine the average strength gain from 7 to 28 to 90 days, as applicable. The data and strength gain evaluations are presented in Attachments C, D, E, and F. The results of a statistical analysis of the test cylinder samples are show in Attachment G (Note: Statistics for Mix T-21510 on Attachment G, Page 5 are for a larger sample discussed later).

Comparison of the two Class 5000 mixes show that they are virtually identical regarding strength and strength development. At 90 days the average compressive strength of the two mixes is within 100 psi and the standard deviations vary by only 20 psi. The 28-day test results show considerable scatter when compared to the expected normal distribution, but the normal distribution curve is a reasonably good fit for the 90-day tests (see Figures 1 & 2). From 28 to 90 days, the standard deviations of both samples decreased significantly. This is possibly an indication of differences due to curing rates or modifications to the mix, and that those differences are not significant after 90 days. The apparent variations from the norm due to testing technique would not be expected to change according to test cylinder age.

Distribution of f'c for Mix DM-5
Quantity of Cylinder Tests in 200 psi Ranges

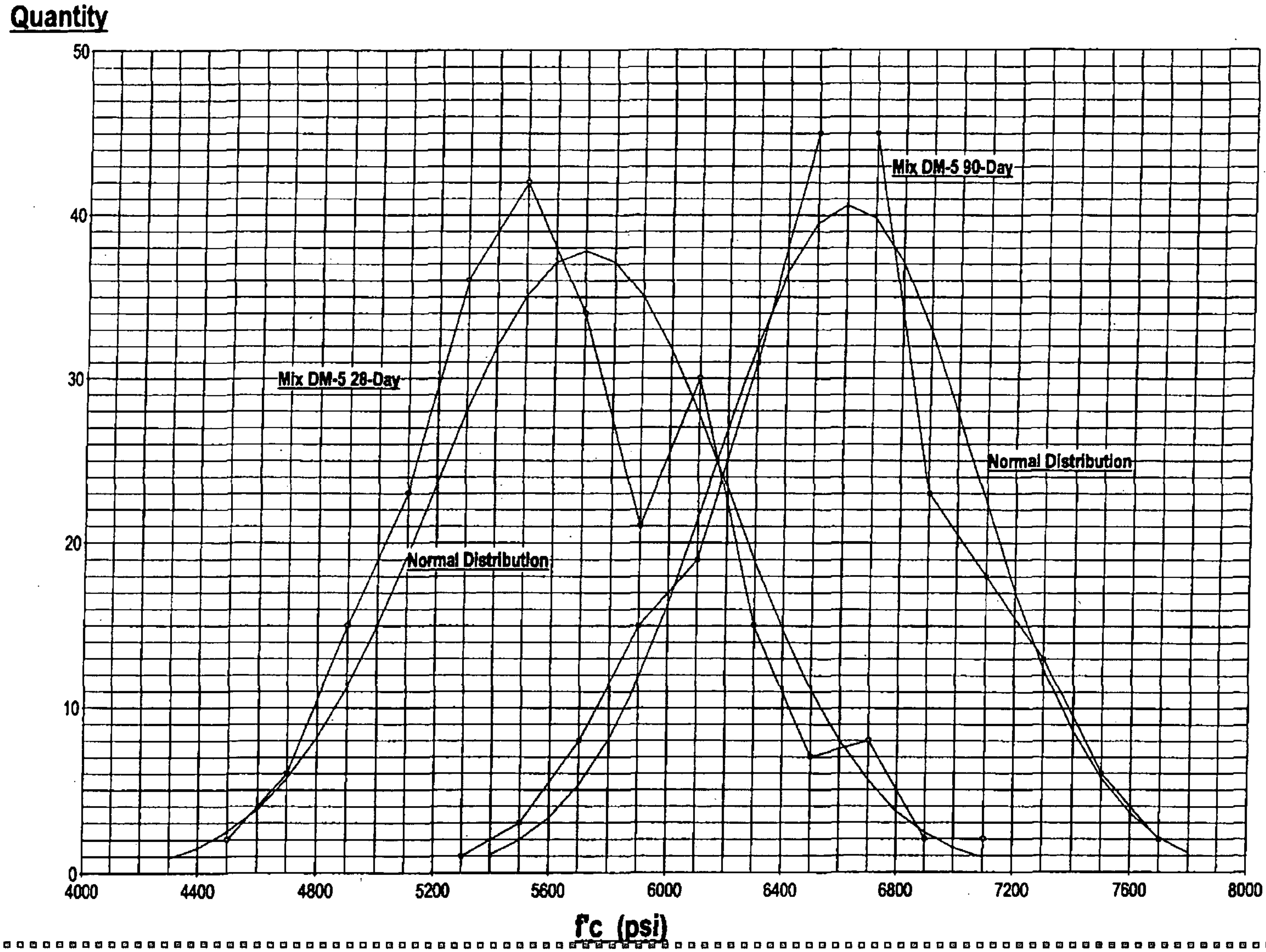

Figure 1 : Mix DM-5 Distribution of f'c

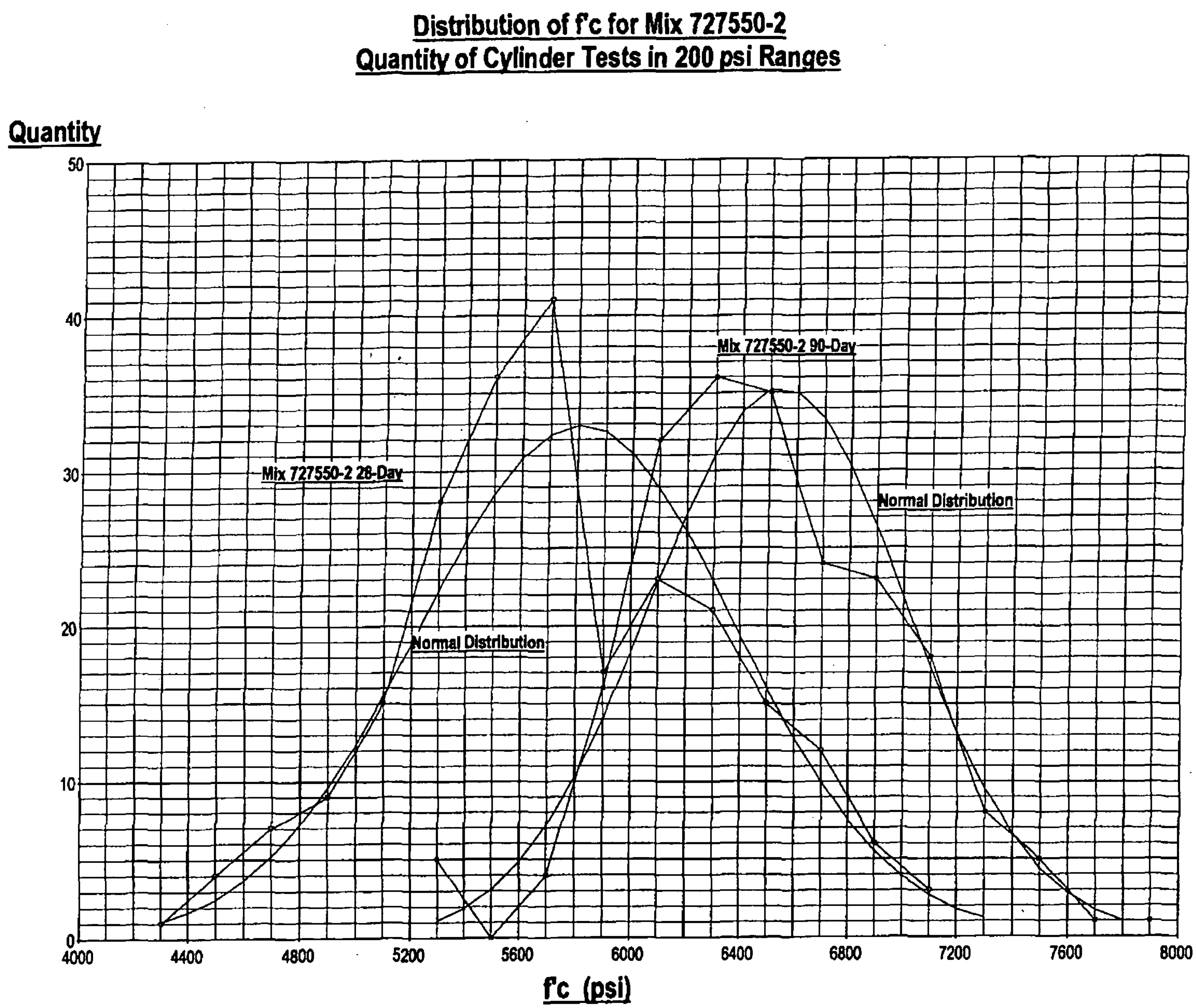

Figure 2 : Mix 727550-2 Distribution of f'c

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Figure 3 shows the average strength gains for the samples analyzed in Attachments C through F. The data in the attachments show the strength gain ratios for each set of cylinders, cured under the same conditions. The average of the gain ratios from the cylinder sets is slightly higher than the gain ratio calculated the average strengths of the samples for all of the samples. The more conservative (lower) gain ratios calculated from average compressive strengths are presented in Figure 3 and the table below.

	Days	Avg. f'c	f'c-90 / f'c-28
Mix DM-5	7	4265	
(Attachment D)	28	5641	
	90	6558	1.16
Mix 727550-2	7	4249	
(Attachment E)	28	5791	
	90	6489	1.12
Mix T-21510	7	2911	
(Attachment C)	28	4535	
DHP Pours 28 & 29	7	2808	
(Attachment F)	28	4340	
	90	5805	1.34

Although the differences between the two Class 5000 concrete mixes are not statistically significant, the strength gain from 28 days to 90 days will be conservatively considered to follow the Mix 727550-2 curve due to its slightly flatter slope. The gain from 28 days to 90 days for Class 5000 concrete is 12%.

Comparison of the data for Mix T-21510 from Attachment C to the data from the two pours in the Decay Heat Pit (Attachment F) for the same concrete mix leads to the conclusion that Pours 28-DHP and 29-DHP are representative of all of the Class 3000 concrete. The strength gain from 7 to 28 days is parallel for both samples, so a projection of the T-21510 sample average compressive strength at 28 days out to a 90-day compressive strength based on the two DHP pours is justified. A conservative straight-line extrapolation of the T-21510 data would give a 90-day compressive strength of approximately 5900 psi, as shown on Figure 3. That is equivalent to a gain from 28 days to 90 days of

$$(5900 - 4535) / 4535 = 30\%$$

The straight line extrapolation is considered conservative because it results in lower gain ratio than the data from the two DHP pours.

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Compressive Strength vs. Time

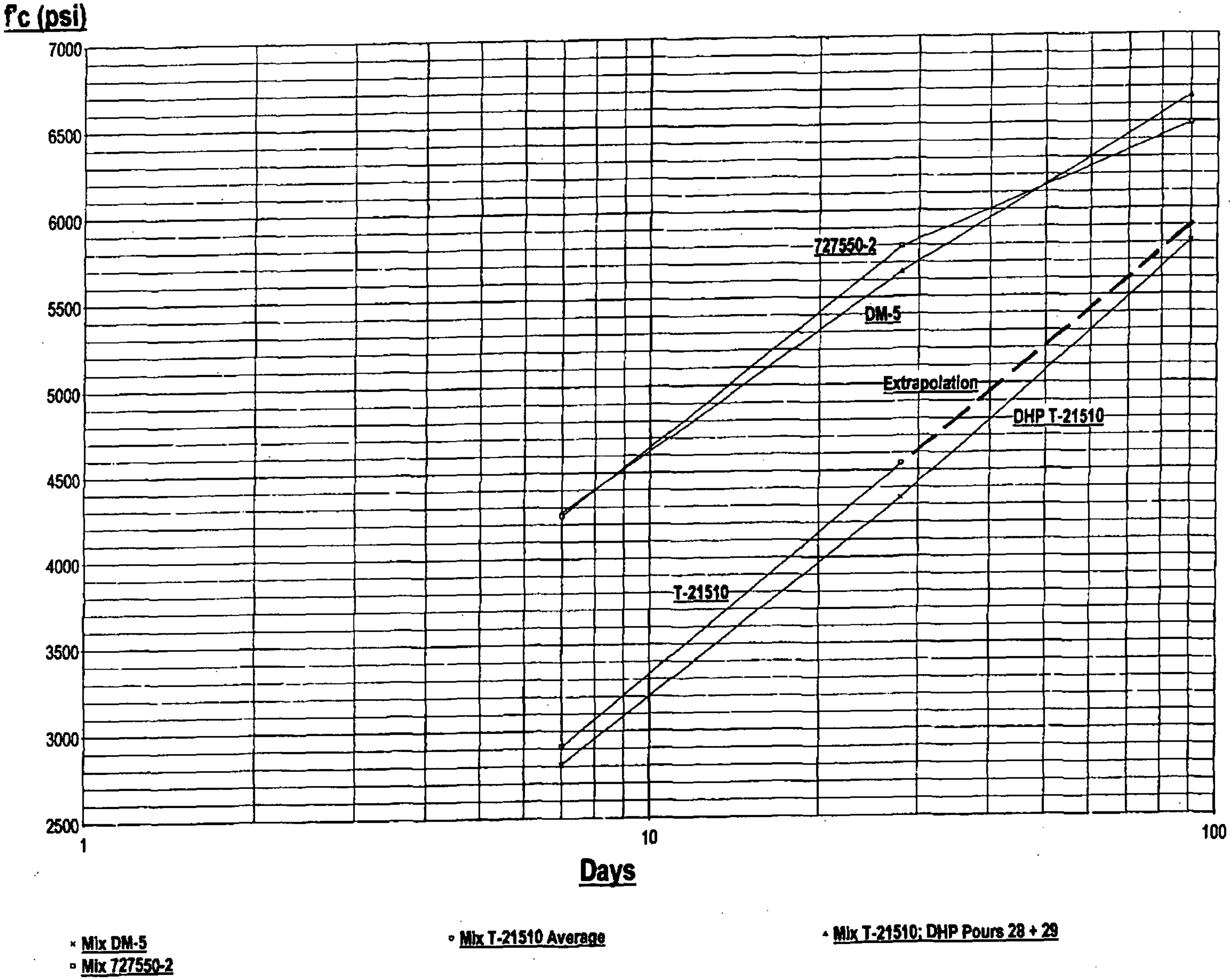

Figure 3 : Strength Gain for CR3 Concrete

B. Post 90-Day Strength Gain

The rate of compressive strength gain for a typical concrete made from Type II cement is shown in ACI 225R-91 Fig. 6.1 (Ref. 7):

Typical Strength Development for Type II Cement		
Time		
Days	Yrs	f'c
7		2550
28		3450
90		4200
180		5200
365	1	5650
730	2	6200
1095	5	6500

Note: Fig. 6.1 in ACI 225R-91 has mislabeled the time axis, showing the 5 year data as 3 years. The error is apparent if the data is plotted to scale. The "Concrete Construction Handbook" (Ref. 12) presents the same graph showing the data at 5 years.

The comparison of the three CR3 mixes to the typical Type II curve is shown in Figure 4. All of the CR3 mixes have a higher rate of strength gain from 28 days to 90 days than the ACI curve. The CR3 concrete mixes are higher strength than the typical Type II data.

Higher-strength concrete would be expected to gain strength more quickly than lower strength concrete. The use of admixtures could also affect the rate of strength gain. Therefore, deviations of sample data from the typical curve would be expected, but differences might be expected to diminish with time. After 90 days the strength gain due to aging should be similar for concretes made from the same type of cement. This would be indicated on a graph such as Figure 4 by parallel lines. More scatter would be expected for data from early ages, with a trend toward more consistency with increasing time.

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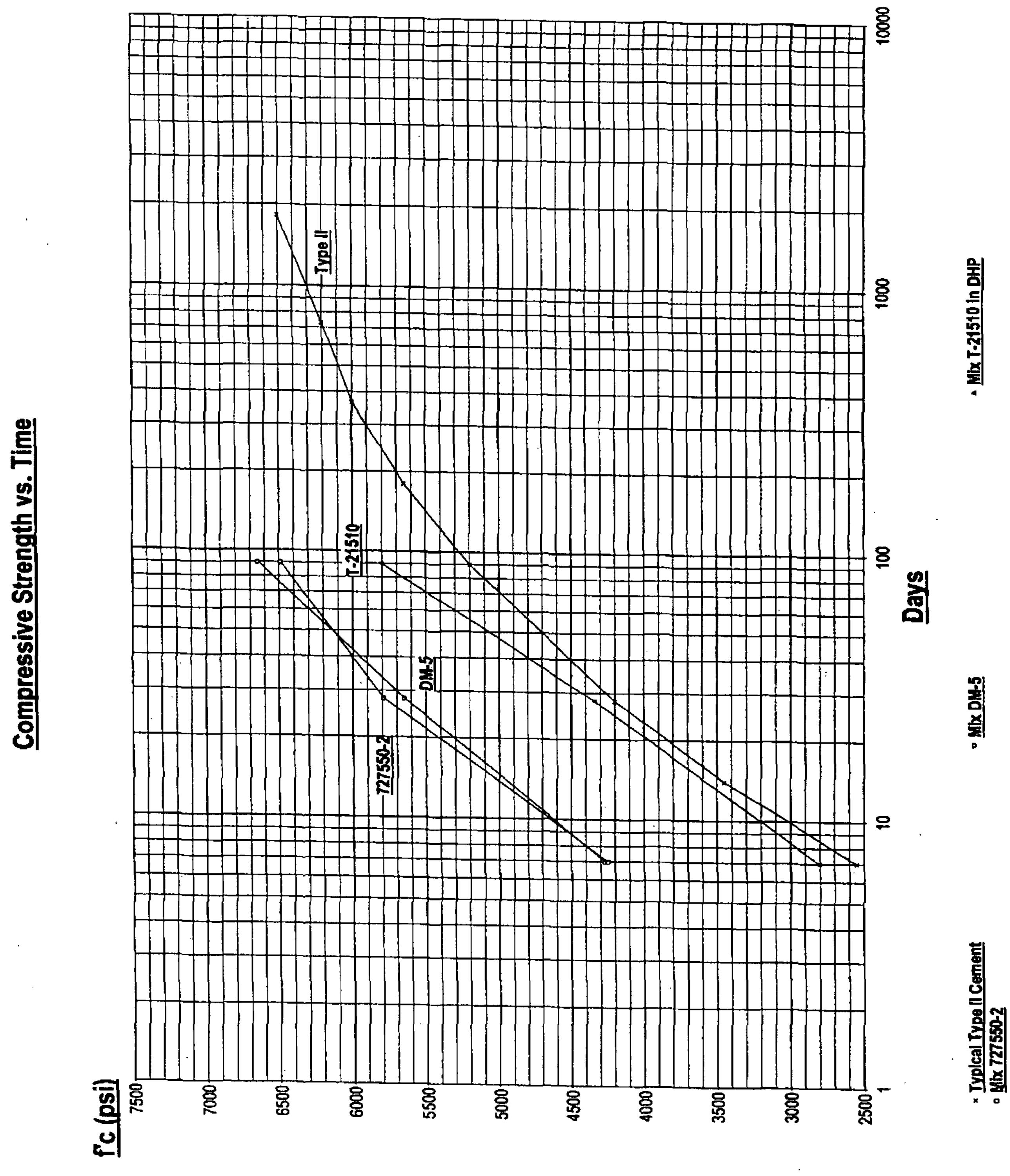
Figure 4 : Strength Gain for Typical Type II Cement Mixtures



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To eliminate the effects of different design compressive strengths on the comparison, the data has been normalized to 90 days and replotted in Figure 5. The data as presented in this format show a reasonable agreement with the typical Type II curve when consideration is given to the higher early strength gain expected for higher strength mixes. Although the data, by definition, converge at 90 days due to normalization, the trend agrees with the typical Type II cement curve.

The typical Type II cement curve from ACI shows a strength gain from 90 days to 5 years of 25%. A conservative extrapolation of the data from the CR3 mixes past 90 days, giving consideration to the decreasing slope of the strength gain curve, leads to the conclusion that a 20% strength gain from 90 days to 5 years could reasonably be expected for CR3 concrete.

Concrete strength gains due to aging have been documented to occur out to 50 years. However, after about 5 years the strength gains become small and relevant data in the literature was not located. Neglecting strength gains that may occur after 5 years is conservative. The earliest Class I concrete pours at CR3 were started in June 1970. The major structural elements were completed by early 1976. Given the age of the CR3 concrete, a strength gain of 20% from 90 days to the present would appear to be a conservative projection, based on the supporting data.

Compressive Strength Normalized to 90-Days

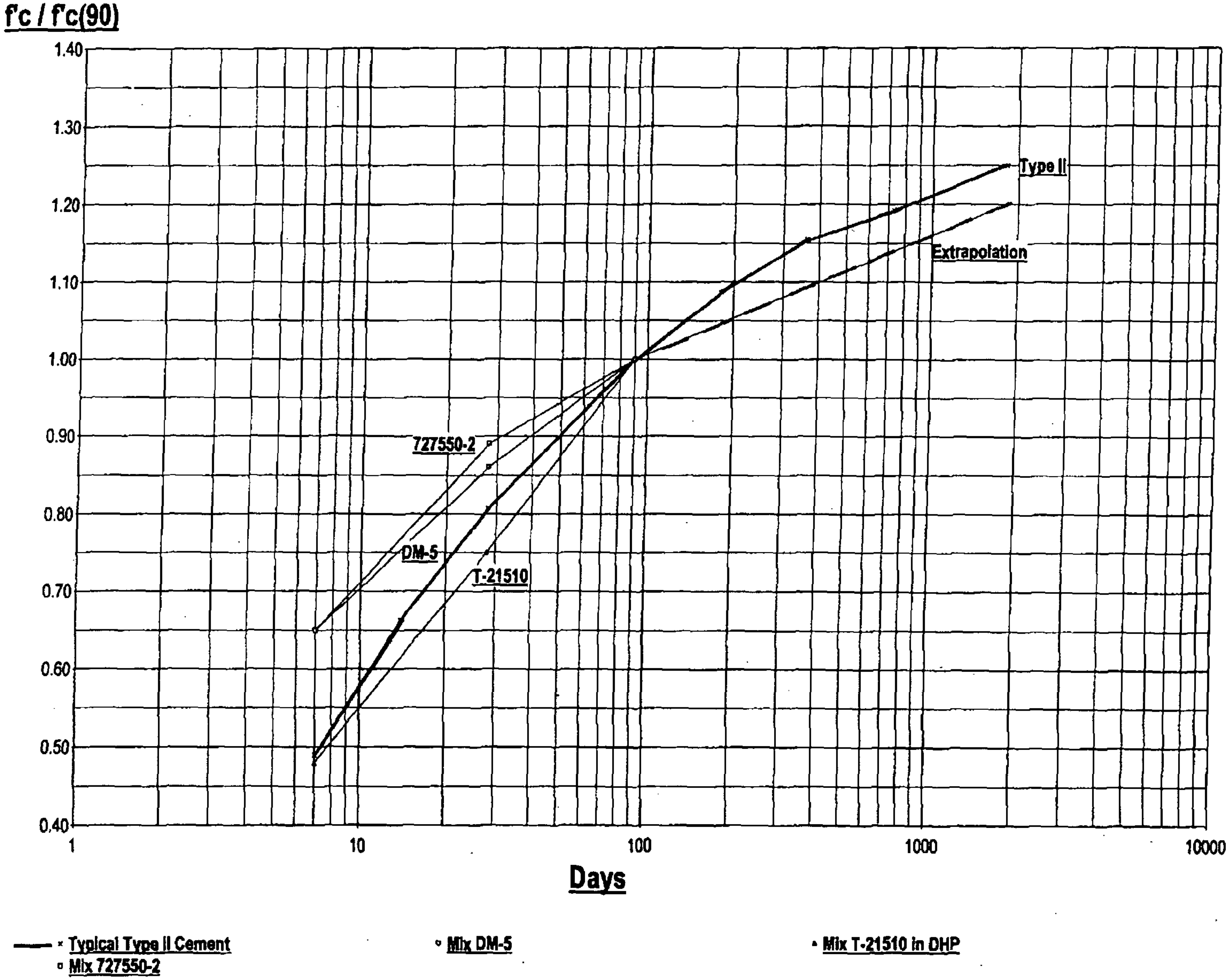

Figure 5 : Compressive Strength Normalized to 90 Days

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C. Discussion of Conservatism

The compressive strength vs. time curve for concrete has been approximated by straight line segments on a semi-logarithmic graph. Based on existing test data, extrapolations, and comparison with typical concrete aging data in the literature, the slopes of the line segments (or "gain ratios") have been conservatively determined. For the purposes of this calculation, a conservative gain ratio is one that results in a lower compressive strength. The conservatism for each gain ratio has been previously discussed.

The strength vs. time curve that is represented by the line segments describes the behavior of **average** compressive strength (designated as $f_{c\ Avg}$). The CR3 cylinder test data and the typical Type II cement curve from which the gain ratios were determined use average concrete strength from cylinder compression tests.

ACI codes require that concrete mixes be selected such that the average compressive strength required (f'_{cr}) exceeds the compressive strength used for design (f'_c). This is done so that only a statistically small amount of concrete would be expected to be understrength. The margin required is related to the standard deviation "s" of the results of a population of cylinder tests for the proposed mix. The more restrictive of the following two requirements applies:

$$f'_{cr} = f'_c + 1.34\ s$$

or

$$f'_{cr} = f'_c + 2.33\ s - 500$$

If the standard deviation of the selected mix is known and assumed to remain constant for jobs with good quality control, then the margin required for both requirements above is essentially a multiple of s. For simplicity, the margin will be considered as 1.34 s for the remainder of this discussion.

After concrete has been placed and cylinder tests have been completed, $f_{c\ Avg}$ and s are known. The maximum design compressive strength that can be credited can be found by rearranging the equation, using $f_{c\ Avg}$ for f'_{cr}:

$$f'_c = f_{c\ Avg} - 1.34\ s$$

Typically the design strength f'_c for concrete is specified at 28 days. If the long-term design strength is predicted using "gain ratios" derived from average strength data, the result will be conservative because of the 1.34 s term in the above equation.

Consider the following example, for a concrete with 28-day test results of $f_{c\ Avg}$ = 5670 psi and s = 500 psi (s assumed constant over time). The 28-day design strength is back-calculated as

$$f'c = 5670 - 1.34 \times 500 = 5000 \text{ psi}$$

In the table below, the 90-day and 5-year values of $f_{c\ Avg}$ and f'_c are predicted using the gain ratios shown, and the third column is calculated from $f_{c\ Avg}$ and the constant s.

t	Gain Ratio	fc Avg	Predicted f'c	fc Avg - 1.34 s
28 days		5670	5000	5000
90 days	1.12	6350	5600	5680
5 yrs	1.20	7620	6720	6950

Figure 6 shows the conservatism that results from predicting f'c using average strength gain ratios. If the gain ratios properly predict the average strength of the concrete and the standard deviation of the sample remains constant, the design compressive strength that could be utilized is represented by the line parallel to the average strength curve, and is always (1.34 x s) less than the average strength. The predicted f'c curve is always lower, and the difference becomes greater if larger gain ratios are utilized for any line segment. Note that the 28 to 90-day gain ratio for Class 3000 concrete was determined to be 1.30.

The discussion above has considered that the standard deviation is constant over time. As noted previously when evaluating the test result sample population statistics for Class 5000 concrete, the standard deviations decreased significantly between 28 and 90 days. This is reasonable as small differences in curing rates would be expected to diminish with time, and the sample population would therefore become more uniform. If s decreases with time then the term (1.34 x s) also decreases, which results in a larger difference (more conservative) between the predicted design compressive strength and the maximum value that could be utilized.

Summarizing the discussion above:

Use of the conservative average compressive strength "gain ratios" to predict long term design strength results in even more conservatism.

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Figure 6 : Example Showing Conservatism of Strength Projections

Compressive Strength vs. Time

Example showing conservatism when Design f'c is projected from 28 days