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Seismic design
Ground motion
Site response
Seismology

EPRI TR-100082
Tier 1
Project 3096-1
Final Report
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# Standardization of the Cumulative Absolute Velocity



Prepared by
Yankee Atomic Electric Company
Bolton, Massachusetts

R E P O R T   S U M M A R Y

# Standardization of the Cumulative Absolute Velocity

The cumulative absolute velocity (CAV) is a measure of the damage potential of earthquake ground motion and is part of the EPRI exceedance criterion for the operating basis earthquake. Standardization of this measure will enable utility engineers to calculate CAV without arriving at unduly high values driven by parts of the seismic record that are not damaging.

**INTEREST CATEGORIES**

Nuclear seismic risk, design, and qualification
Nuclear component reliability
Nuclear plant operations and maintenance

**KEYWORDS**

Earthquakes
Seismic design
Ground motion
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Seismology

**BACKGROUND** Small earthquakes in the eastern United States have occurred with ground-motion amplitudes sufficient to exceed the design-response spectrum for the operating basis earthquake (OBE). Recognizing the threat of future events, EPRI recently developed a report (NP-5930) defining a two-level criterion that requires an evaluation of the recorded-response spectrum and a new parameter, the CAV. CAV was defined as the integration of the absolute value of ground acceleration over the seismic time-history record. On the basis of an examination of more than 250 seismic records, the panel made up of utility, NRC, and industry experts set the threshold of the CAV parameter for OBE exceedance to correspond to the onset of potential damage to buildings of good design and construction. With this criterion, nuclear power plants would not be subject to unnecessary shutdown in response to an earthquake event. However, project investigators noted that the long seismic records often contained a significant portion of small-amplitude, nondamaging motion. These long "tails" (or coda) contributed to the CAV value and made the CAV measurement dependent on the seismic recording device and its particular shut-off mechanism and threshold.

**OBJECTIVE** To remove the CAV measurement dependence on the duration of low-amplitude, nondamaging portions of recorded ground motion.

**APPROACH** Project investigators reviewed nearly 300 seismic records, including the entire earthquake data set examined for report NP-5930. They evaluated various means of truncating long seismic records containing nondamaging motions to arrive at a stable estimate of CAV. They compared results with those of the previous study and reevaluated the threshold value for OBE exceedance.

**RESULTS** A stable and robust measure of CAV has been derived from an examination of the seismic record in discrete time intervals of one second each. A threshold value of acceleration has been defined as the basis for accepting or rejecting each interval in the CAV calculation. In this manner, portions of the seismic record having low, nondamaging accelerations do not contribute to the CAV, and its calculated value is essentially independent of the recording device used to obtain the record. Report TR-100082, tier 1, summarizes the project; tier 2 provides a detailed analysis and discussion of the results.

**EPRI PERSPECTIVE** Past experience has shown that the threat of an unnecessary, expensive plant shutdown following nondamaging earthquake ground motions applies especially to plants in the eastern United States, where high-frequency, low-energy earthquake ground motions may exceed design spectra. Such ground motions do not damage buildings of good design and construction, especially seismically rugged nuclear power plant structures and equipment. The addition of the CAV parameter to the OBE exceedance criterion presents a practical solution to the problem of determining whether a future earthquake may cause damage.

The standardization of the CAV provides the needed assurance that its measure will not depend on the manner in which the ground-motion data are acquired; that is, ground-motion records of unusually long duration will not contribute to an overestimate of the CAV value that is used, together with the response spectrum, to determine OBE exceedance.

The report is a follow-on to report NP-5930, in which the two-level OBE criterion is defined. A related report, NP-6695, presents guidelines for nuclear plant response to an earthquake.

**PROJECT**

RP3096-1

Project Manager: John F. Schneider

Nuclear Power Division

Contractor: Yankee Atomic Electric Company

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# Standardization of the Cumulative Absolute Velocity

**TR-100082, Tier 1**
**Research Project 3096-1**

Final Report, December 1991

Prepared by
YANKEE ATOMIC ELECTRIC COMPANY
580 Main Street
Bolton, Massachusetts 01740

Principal Investigators
T. F. O'Hara
J. P. Jacobson

Prepared for
**Electric Power Research Institute**
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
J. Schneider

Nuclear Seismic Risk Program
Nuclear Power Division

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ABSTRACT

EPRI NP-5930, " A Criterion for Determining Exceedance of the Operating Basis Earthquake," was published in July 1988. As defined in that report, the Operating Basis Earthquake (OBE) is exceeded when both a response spectrum parameter and a second damage parameter, referred to as the Cumulative Absolute Velocity (CAV), are exceeded.

In the review process of the above report, it was noted that the calculation of CAV could be confounded by time history records of long duration containing low (nondamaging) acceleration. Therefore, it is necessary to standardize the method of calculating CAV to account for record length. This standardized methodology allows consistent comparisons between future CAV calculations and the adjusted CAV threshold value based upon applying the standardized methodology to the data set presented in EPRI NP-5930. The recommended method to standardize the CAV calculation is to window its calculation on a second-by-second basis for a given time history. If the absolute acceleration exceeds 0.025g at any time during each one second interval, CAV, for that second, is calculated and summed. Using this methodology, the earthquake records used in EPRI NP-5930 have been reanalyzed and the adjusted threshold of damage for CAV was found to be 0.16g-sec.

This is a report summary (Tier 1); detailed analysis and discussion of results are given in EPRI TR-10082 (Tier 2).

ACKNOWLEDGEMENTS

This work was funded by the Electric Power Research Institute, under Project RP3096-01. John Schneider was the project manager and provided valuable guidance and suggestions. Robert P. Kennedy and John W. Reed reviewed preliminary and final results, made valuable suggestions and gave direction to this study. Particular thanks goes to John W. Reed for providing Yankee with the computer program and time histories used in EPRI NP-5930.

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## ILLUSTRATIONS

## Section 1
## INTRODUCTION

### 1.1 BACKGROUND

In recognition of the need to develop a rational criterion for determining when the OBE has been exceeded at a nuclear power plant and, hence, when actions are required in accordance with 10CFR100, Appendix A, the Electric Power Research Institute (EPRI) formed an OBE Exceedance Working Panel. The panel, which consisted of industry consultants as well as nuclear utility and NRC representatives, developed a two-level criterion for determining OBE exceedance which is published in EPRI Report NP-5930 (1).

This two-level criterion contains both a response spectrum check and a Cumulative Absolute Velocity (CAV) check. Using this criterion, the OBE is considered to have been exceeded if:

1. Response Spectrum Check: The 5% damped ground response spectrum for the earthquake motion at the site at frequencies between 2 and 10 Hz, exceeds the corresponding OBE design response spectrum or 0.20g, whichever is greater;

AND

2. CAV Check: The computed CAV value from the earthquake record is greater than 0.30g-sec.

The new parameter introduced is referred to as the CAV. It should be noted that for some time, earthquake engineers have struggled with the problem of defining a single parameter that relates measured ground motion to potential structural damage. In (1) several parameters such as peak ground acceleration, Arias intensity, root mean square (rms) acceleration, and many others, along with CAV, were evaluated in the process of selecting a meaningful parameter that could be used for predicting the threshold of potential damage. It was concluded in (1) that CAV is the best single parameter for determining the damage threshold of earthquakes. In addition, it was determined that a CAV value of 0.30g-sec conservatively defines the threshold of damage for nuclear power plant structures and equipment. CAV is an optional second check when the response spectrum check leads to an exceedance.

The CAV was originally defined as follows (1):

$$CAV = \int_0^{t_{max}} |a(t)|d(t) \qquad (1)$$

where:

$a(t)$ = acceleration time history
$t_{max}$ = duration of record

This parameter is the area under the absolute accelerogram and is primarily sensitive to potentially damaging low-frequency motions, but less sensitive to high-frequency motions which are nondamaging.

However, as can be seen on Figure 1-1, the calculation of CAV over the entire length of the time history can produce values that are significantly affected by low nondamaging acceleration (typically less than 0.025g). The time history shown in Figure 1-1 is from the Hollister earthquake, and it defines the threshold of potential damage (1). As can be seen, strong ground motions (acceleration greater than 0.05g) end after about eight seconds, yet CAV continues to be summed for the entire length of record, 56 seconds. The component of CAV between 8 and 56 seconds represents almost 50% of the total calculated CAV; yet, as can be seen, this is simply a function of record length. A longer record length would have led to a larger CAV with no corresponding increase in damage potential. Therefore, it is necessary to develop a methodology to standardize the calculation of CAV such that record length does not confound its significance; that is, the CAV should be calculated for the damaging part of the record only. This standardized methodology will allow consistent comparisons between future CAV calculations and a CAV threshold value determined by applying the standardized methodology to the data set presented in EPRI NP-5930 (1).

## 1.2 APPROACH

Development of a standardized methodology to calculate CAV was performed in two phases. Phase 1 was a preliminary analysis of the first 52 earthquake records used in (1). Alternative methods to calculate CAV were evaluated and, based upon these results, a method to standardize the calculation of CAV was recommended.

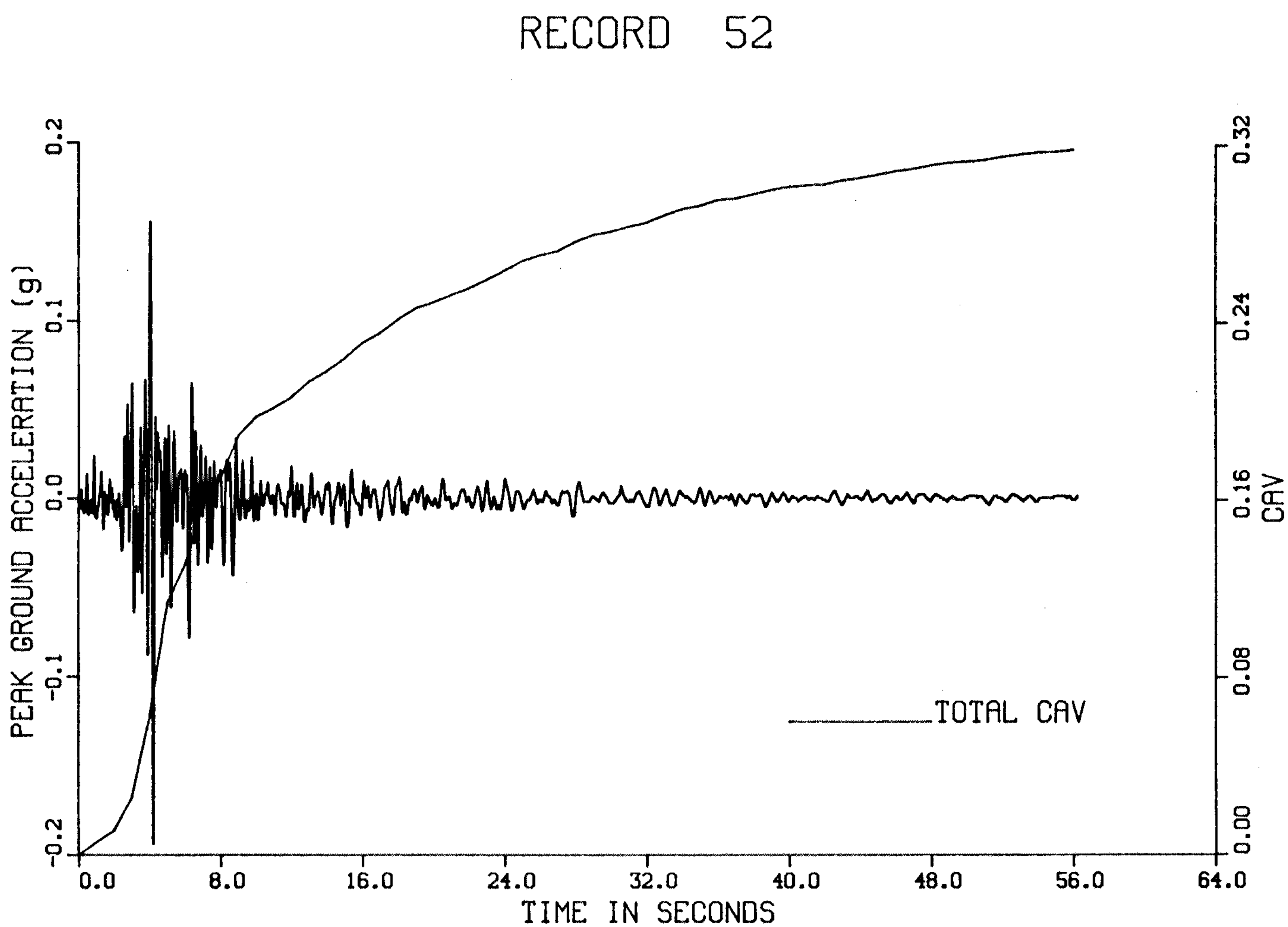



Figure 1-1. Plot of CAV Versus the Hollister Time History to Show the Effect on CAV of Low, Nondamaging Accelerations

The recommendation was reviewed by an Advisory Panel for this study consisting of Dr. Robert Kennedy and Dr. John Reed who developed the original CAV concept (1). Phase 2 was an evaluation of all earthquake records used in (1) minus the Oroville sequence. Elimination of the Oroville sequence was recommended by the Advisory Panel because many of the site intensity values for these earthquakes are not based upon observed intensities but are estimated site intensities. It should be noted that all references to earthquake record numbers in this report are consistent with the earthquake record numbers defined in (1). This report represents a summary of the analyses performed (Tier 1). A more complete report (Tier 2) is given in (2).

Section 2
# ANALYSIS

## 2.1 INTRODUCTION

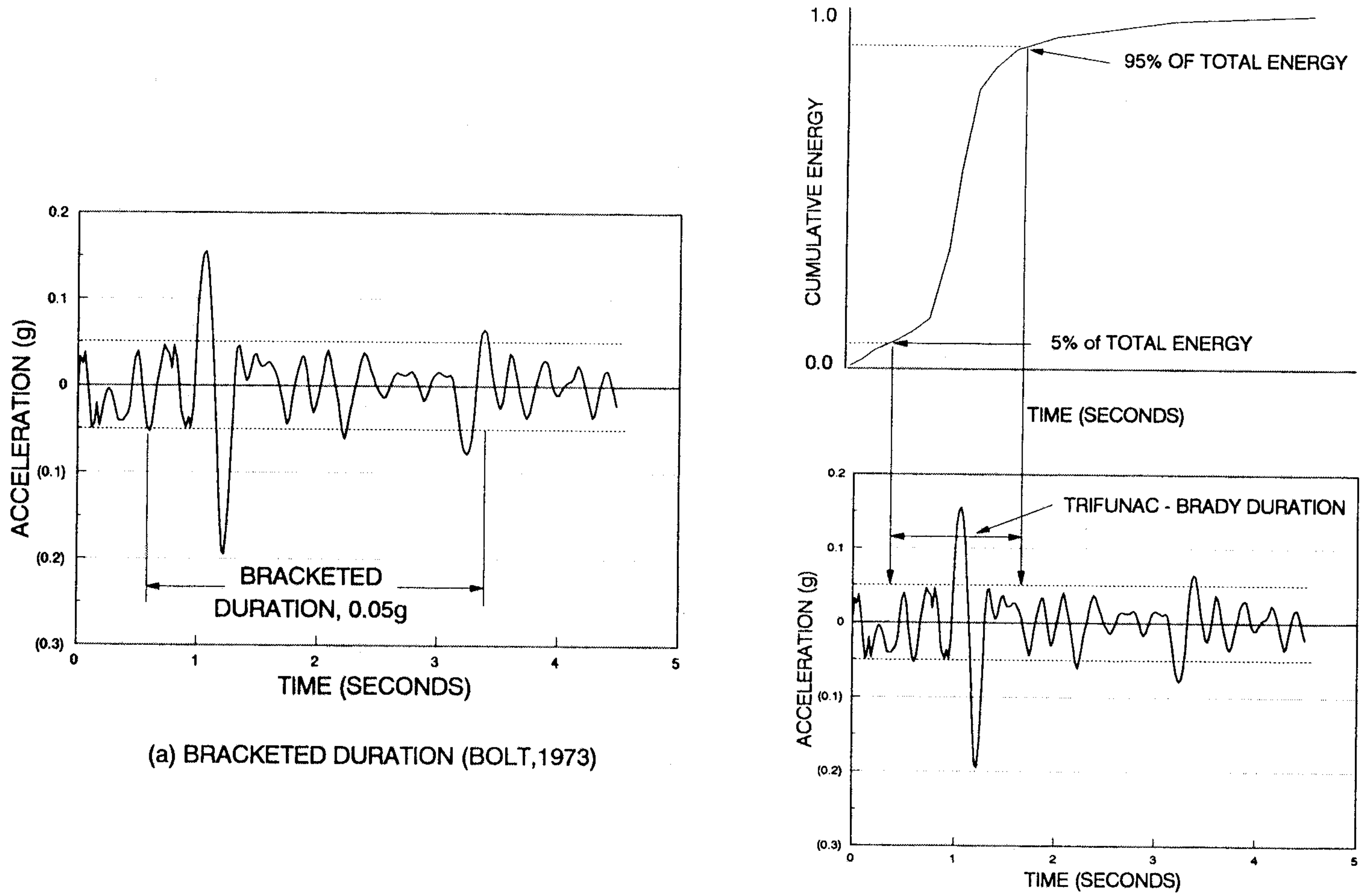
Preliminary analyses were performed on the first 52 records in EPRI NP-5930 (1). The purpose of these analyses was to evaluate different methods of standardizing the start and end times for the calculation of CAV. In effect, these start and end times determine the effective duration of strong ground shaking, which is one of the most important parameters characterizing the severity of an earthquake. This concept of duration is important because, as can be seen from Figure 1-1, the original calculation of CAV (1) is the summation of the CAV associated with the potentially damaging ground motion (about the first eight seconds of ground motion shown on Figure 1-1), as well as the remaining nondamaging tail of the time history.

Several methods have been proposed for characterizing the duration of strong ground shaking. Two of the more widely used, shown in Figure 2-1, are:

- Bracketed Duration: The time between the first and last excursion of the absolute value of acceleration above some threshold level, typically 0.05g (3).
- Trifunac-Brady Duration: The time required for 90% of the total energy (defined as Arias Intensity) to arrive; the duration is defined by the time interval between 5% and 95% of the total recorded energy (4).

Because the objective of this analysis is to define a method to standardize the CAV calculation, and because the above methodologies lend themselves toward this objective, they were used as a starting point in this analysis. These definitions were used initially, and their effect on CAV evaluated, along with several variations in the threshold limits used in the definitions. In particular, variations as suggested by Kennedy (5) were also evaluated.

The results of the preliminary analysis were reviewed by the Advisory Panel. They agreed that the bracketed CAV approach would satisfy the need to standardize the CAV calculation such that the results from future calculations could be consistently compared against the threshold of potential damage. Given the above guidance, all of the records used in EPRI NP-5930 (minus the Oroville sequence) were analyzed using bracket values of 0.015g, 0.020g, and 0.025g.




(a) BRACKETED DURATION (BOLT,1973)

(b) TRIFUNAC AND BRADY DURATION (1975)

Figure 2-1. Illustrations of Bracketed Duration and Trifunac-Brady Duration

The computer code was also modified such that the CAV could be calculated and summed for each one-second interval of the time history where the PGA exceeds the threshold value.

The panel also requested plots using the various measures of bracketed duration be presented for all events with site intensities equal to or greater than VII. With this information, an adjusted threshold of damage value for CAV could then be determined.

## 2.2 METHODOLOGY

The CAV defined in equation (1) is revised to incrementally calculate CAV in one second intervals as follows:

$$CAV_{Total} = CAV_i + \int_{t_{i-1}}^{t_i} |a(t)| \, d(t) \qquad (2)$$

where:

a(t) = acceleration values in a one-second interval where at least one value exceeds 0.025g, and

i = 1, n with n equal to the record length in seconds.

As stated earlier, the Bracketed Duration is typically defined by the time between the first and last excursion of the absolute value of acceleration above some threshold level. Because there are time histories where the strong motion is followed by an extended lull (ground motions less than 0.025g) and then a spike in the ground motion above the threshold value occurs, the simple Bracketed Duration approach will lead to an overestimate of CAV. Therefore, to avoid this problem, the CAV calculation is performed in one-second intervals. For time histories that do not have any extended lulls below the threshold acceleration, the CAV value calculated using the normal Bracketed Duration approach is essentially the same as the CAV value calculated using the modified approach.

The Arias intensity is also calculated for all records. The purpose of this calculation is simply to check the conclusion previously presented in (1) that CAV is the most reliable predictor of potential damage.

2.3 RESULTS

The results of this analysis (including plots) were reviewed by the Advisory Panel, and it was agreed that a 0.025g minimum acceleration be used in the standardized calculation of CAV. Record 281 (Whittier earthquake, site intensity = VII) contains the lowest CAV value for any intensity VII or greater event, and, therefore, in a manner consistent with the procedure used in (1), defines the threshold of potential damage with a CAV value of 0.166g-sec (Figure 2-2). In EPRI-NP 5930(1), analysis of the Whittier earthquake was performed subsequent to the analysis of the original earthquake data base. This was done rather than hold up the completion of the report in order to formally incorporate the new record. In that analysis (1), it was determined that the CAV values for the Whittier earthquake Records 280 and 281 (north-south and east-west components) were 0.362g-sec and 0.280 g-sec, respectively. Since both the CAV and spectral acceleration value for the north-south component exceeded the criterion threshold value, the OBE would be considered to have been exceeded. The CAV value for Record 281 was 0.28g-sec, which suggests that this value should have been used as the threshold of potential damage. However, based on a review of damage data directly, no damage to the Pasadena Power Plant was found. In addition, even though the CAV value for Record 281 was slightly below the 0.30g-sec criterion value, the other component is higher. Therefore, the records in total were considered to be consistent with the criterion, and Record 281 was not used to define the threshold of potential damage to a power facility. Based on the above discussion, use of the Whittier earthquake (Record 281) as the threshold of potential damage to buildings of good design and construction in this analysis is conservative. The Hollister earthquake (Record 52), which defined the threshold of potential damage in (1), has a standardized CAV value of 0.177g-sec (Figure 2-3). It is interesting to note that the total record length of Record 281 is 40 seconds and the total record length of Record 52 is 56 seconds. Using the methodology of simply calculating CAV over the entire record length resulted in a CAV value of 0.28g-sec for Record 281 and 0.32g-sec for Record 52. If Record 281 had had a similar record length of 56 seconds, the calculated CAV would have been about 0.34g-sec, assuming the slope of the total CAV curve shown in Figure 2-2 is constant. This again highlights the need to standardize the CAV calculation. From this analysis, a conservative threshold value of 0.16g-sec is recommended for the standardized CAV.

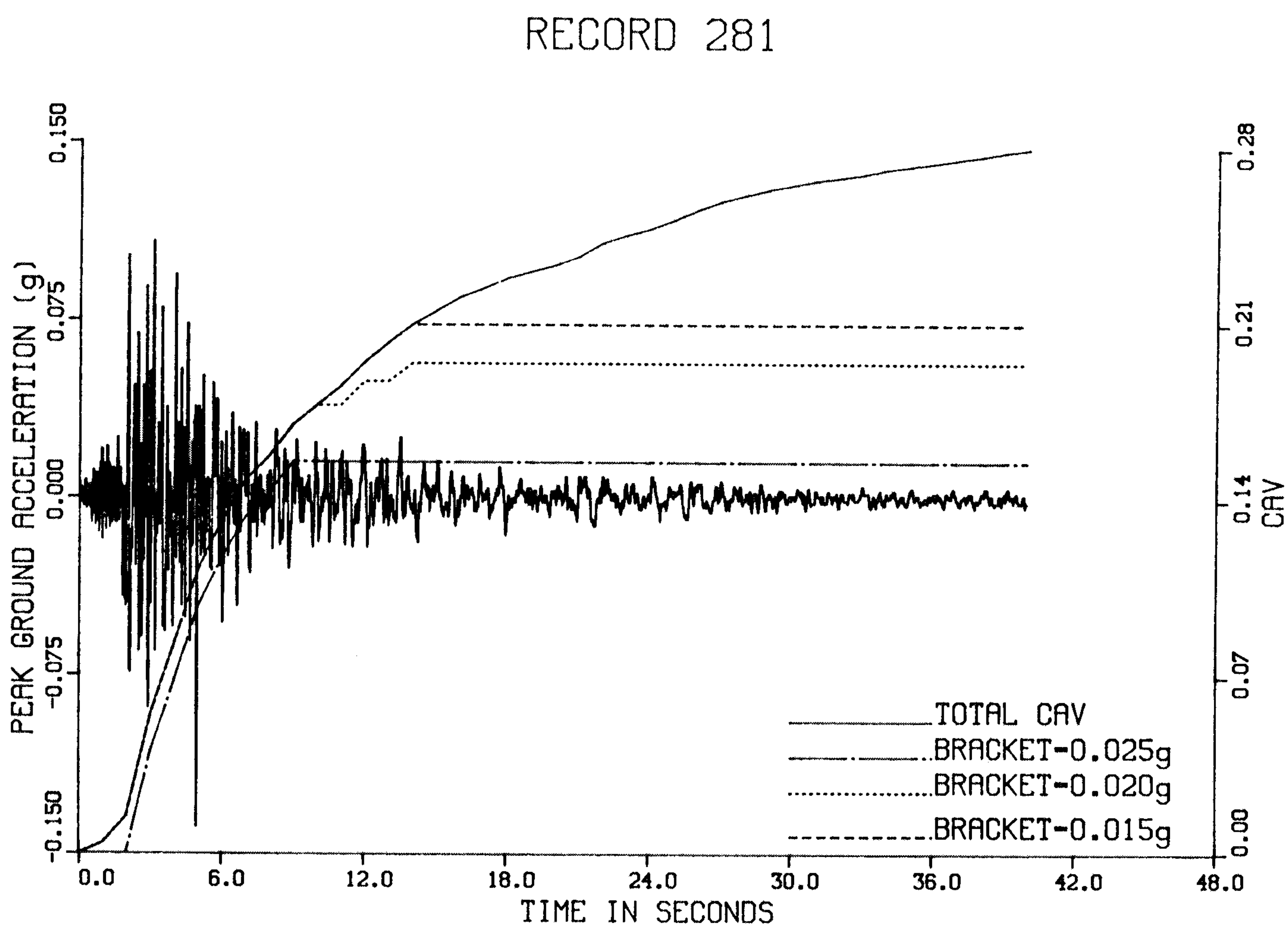



Figure 2-2. Plot of CAV for Record 281 Using the Standardized Method to Calculate CAV

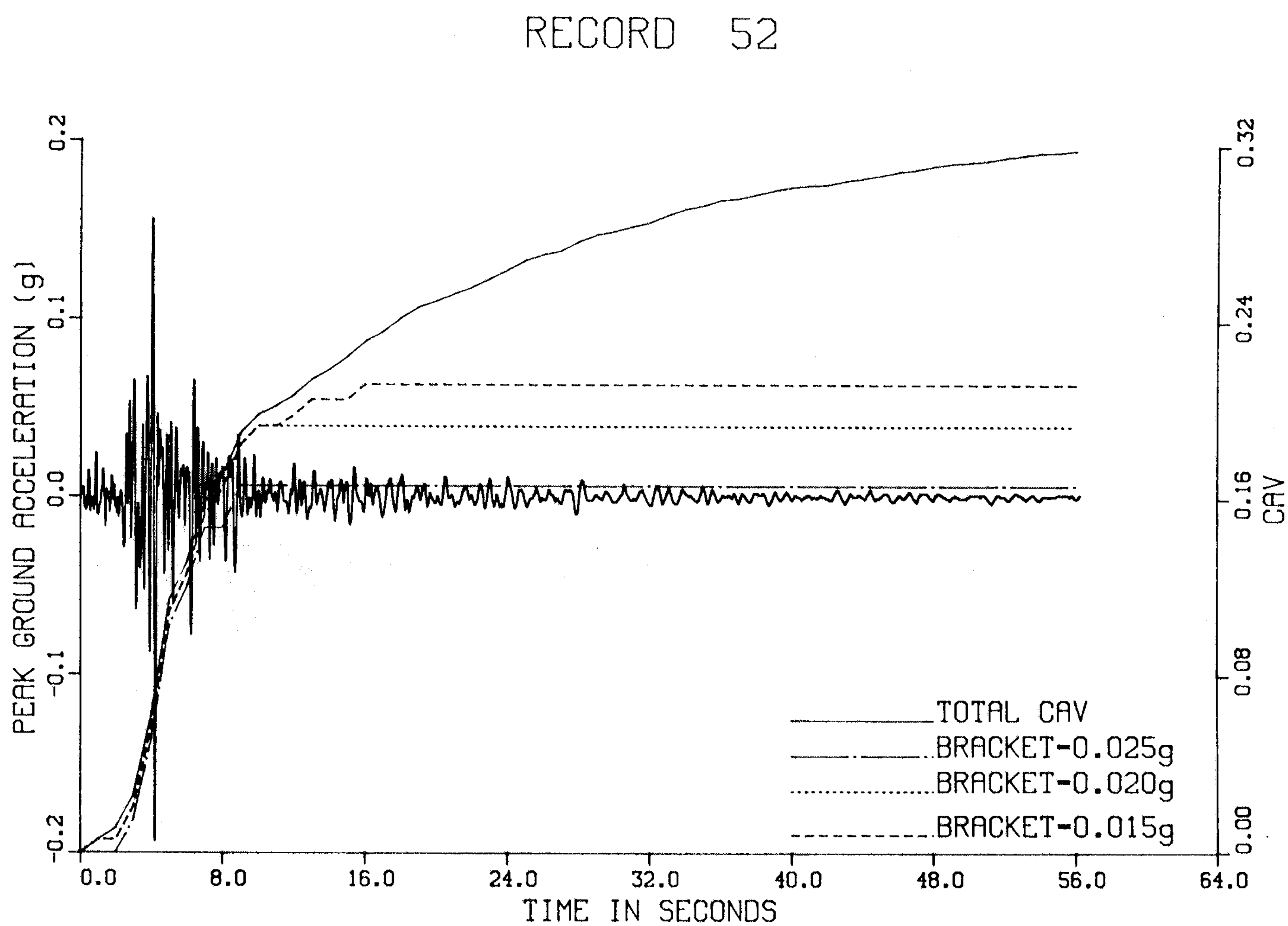



Figure 2-3. Plot of CAV for Record 52 Using the Standardized Method to Calculate CAV

## Section 3
## SUMMARY

### 3.1 METHODOLOGY TO STANDARDIZE THE CALCULATION OF CAV

Based upon the results presented in Sections 2, the Advisory Panel agreed that the calculation of CAV should be standardized by eliminating those portions of the earthquake time history with accelerations less than 0.025g. This is accomplished by analyzing the time history in one-second increments and summing CAV only when the one-second interval contains a ground acceleration greater than 0.025g. Figure 3.1 illustrates this process assuming a sampling rate of 5 samples per second. In a real earthquake record, the data will be analyzed in each one-second interval at the data acquisition sampling rate, usually 100 to 200 samples per second. As can be seen, the first two one-second intervals of the time history shown in Figure 3.1 each contain peak ground accelerations greater than 0.025g and, therefore, CAV is summed for these two seconds. The peak ground acceleration for the third one-second time interval is less than 0.025g and, therefore, the CAV value associated with that one-second interval is discarded. This process is followed for the remainder of the time history resulting in a CAV value of 0.062g-sec.

### 3.2 ADJUSTED CAV THRESHOLD OF POTENTIAL DAMAGE

The adjusted CAV threshold of potential damage is 0.16g-sec. This value was determined by the Whittier earthquake (Record 281) which has the lowest CAV value associated with an earthquake of Intensity VII. Because of arguments presented in (1), use of record 281 to define the threshold of potential damage should be considered conservative. The adjusted CAV threshold is about a factor of five lower than the lowest CAV value associated with documented damage to an industrial/power facility. It is about a factor of three lower than the lowest CAV value associated with documented damage to buildings of good design and construction.

Lastly, it should be noted that a primary reason for development of the CAV criterion (1) was to respond to the potential inconsistency associated with small local earthquakes occurring near EUS nuclear power plants and consequent OBE exceedance necessitating plant shutdown. In all cases, for those records in the data base consistent with the above scenario (small, local, and eastern United States events), the threshold of potential damage is not exceeded.

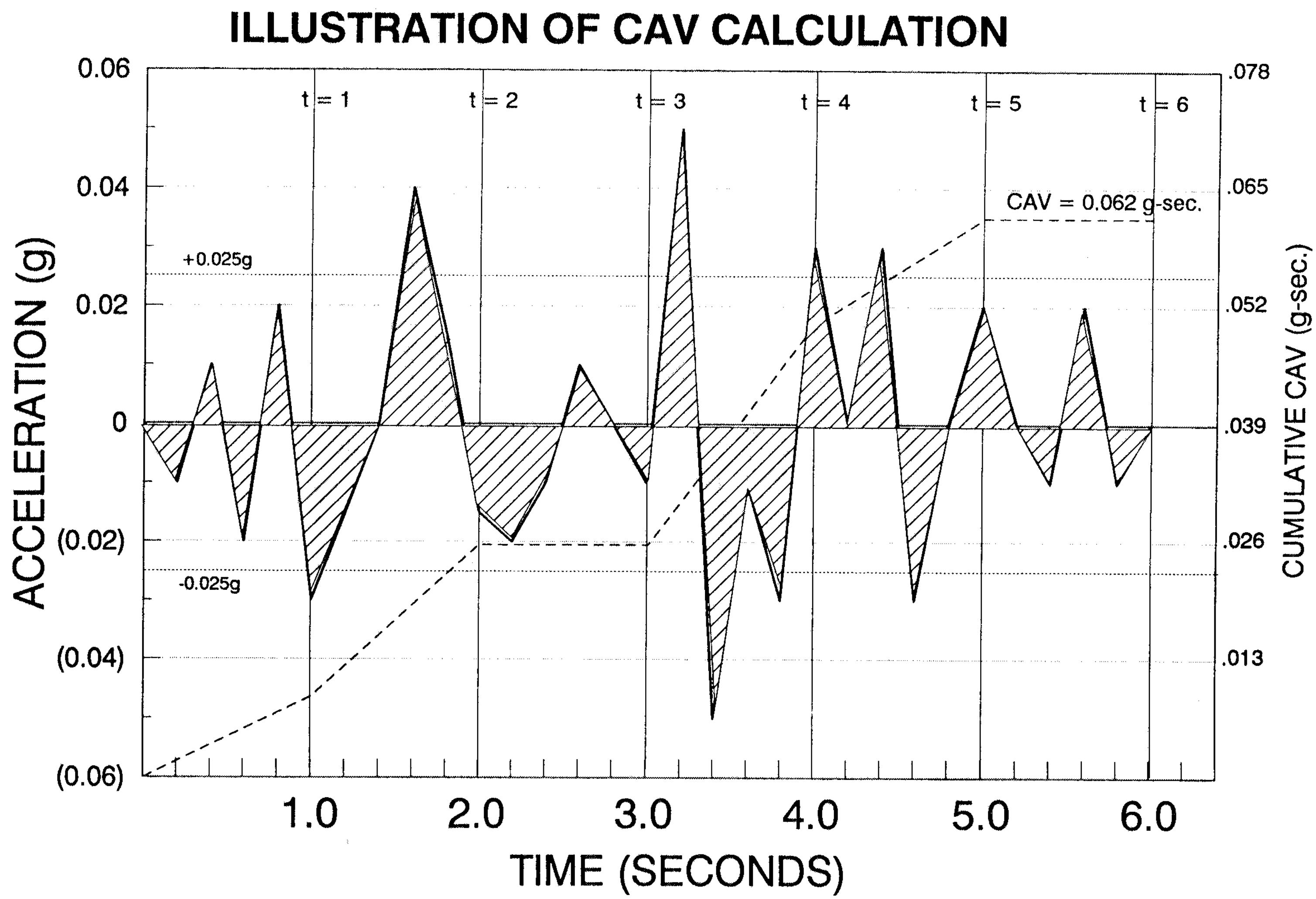



Figure 3-1. Illustrations of the Standardized Method to Calculate CAV

## Section 4
## REFERENCES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