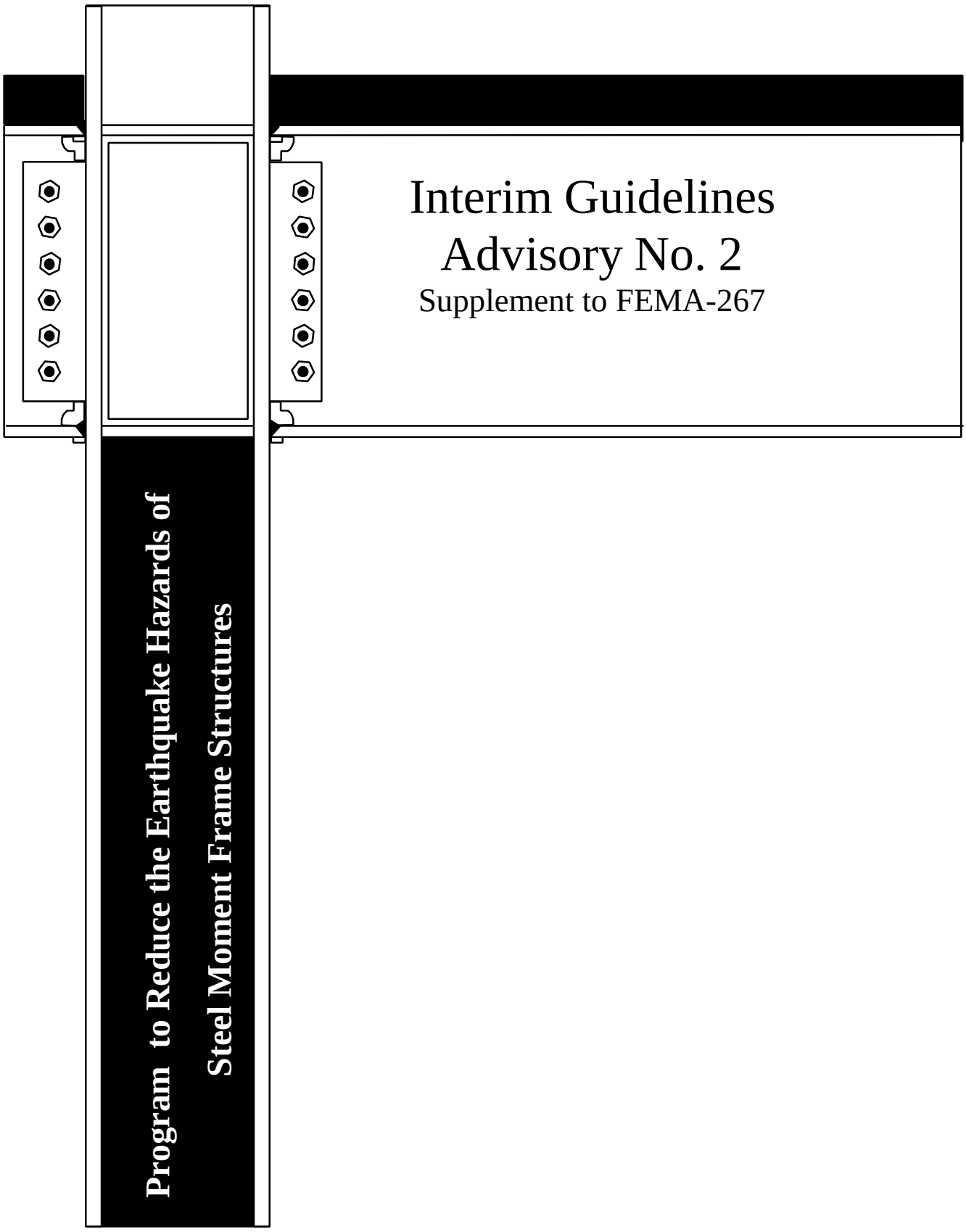

Interim Guidelines Advisory No. 2

Supplement to FEMA-267

Program to Reduce the Earthquake Hazards of Steel Moment Frame Structures

INTERIM GUIDELINES ADVISORY NO. 2

Supplement to FEMA-267 Interim Guidelines:

Evaluation, Repair, Modification and Design of Welded Steel Moment Frame Structures

Report No. SAC-99-01

SAC Joint Venture

a partnership of:
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Applied Technology Council (ATC)
California Universities for Research in Earthquake Engineering (CUREe)

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THE SAC JOINT VENTURE

SAC is a joint venture of the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and California Universities for Research in Earthquake Engineering (CUREe,) formed specifically to address both immediate and long-term needs related to solving problems of the Welded Steel Moment Frame (WSMF) connection that became apparent as a result of the 1994 Northridge earthquake. SEAOC is a professional organization composed of more than 3,000 practicing structural engineers in California. The volunteer efforts of SEAOC's members on various technical committees have been instrumental in the development of the earthquake design provisions contained in the *Uniform Building Code* as well as the *National Earthquake Hazards Reduction Program (NEHRP) Provisions for Seismic Regulations for New Buildings.* The Applied Technology Council is a non-profit organization founded specifically to perform problem-focused research related to structural engineering and to bridge the gap between civil engineering research and engineering practice. It has developed a number of publications of national significance including ATC 3-06, which serves as the basis for the *NEHRP Recommended Provisions.* CUREe is a nonprofit organization formed to promote and conduct research and educational activities related to earthquake hazard mitigation. CUREe's eight institutional members are: the California Institute of Technology, Stanford University, the University of California at Berkeley, the University of California at Davis, the University of California at Irvine, the University of California at Los Angeles, the University of California at San Diego, and the University of Southern California. This collection of university earthquake research laboratory, library, computer and faculty resources is among the most extensive in the United States. The SAC Joint Venture allows these three organizations to combine their extensive and unique resources, augmented by subcontractor universities and organizations from around the nation, into an integrated team of practitioners and researchers, uniquely qualified to solve problems related to the seismic performance of WSMF structures.

DISCLAIMER

The purpose of this document is to serve as a supplement to the *FEMA-267* publication *Interim Guidelines: Evaluation, Repair, Modification and Design of Welded Steel Moment Frame Structures.* This Advisory, which is intended to be used in conjunction with *FEMA-267,* supercedes and entirely replaces *Interim Guidelines Advisory No. 1* (*FEMA 267a*). *FEMA-267* was published to provide engineers and building officials with guidance on engineering procedures for evaluation, repair, modification and design of welded steel moment frame structures, to reduce the risks associated with earthquake-induced damage. The recommendations were developed by practicing engineers based on professional judgment and experience and a preliminary program of laboratory, field and analytical research. This preliminary research, known as the SAC Phase 1 program, commenced in November, 1994 and continued through the publication of the *Interim Guidelines* document. This *Interim Guidelines Advisory No. 2,* which updates and replaces *Interim Guidelines Advisory No. 1,* is based on supplementary data developed under a program of continuing research, known as the SAC Phase 2 program, as well as findings developed by other, independent researchers. Final design recommendations, superceding both *FEMA-267* and this document are scheduled for publication in early 2000. Independent review and guidance in the production of both the *FEMA-267, Interim Guidelines* and the advisories was provided by a project oversight panel comprised of experts from industry, practice and academia. Users are cautioned that research into the behavior of these structures is continuing. Interpretation of the results of this research may invalidate or suggest the need for modification of recommendations contained herein. **No warranty is offered with regard to the recommendations contained herein, either by the Federal Emergency Management Agency, the SAC Joint Venture, the individual joint venture partners, their directors, members or employees. These organizations and their employees do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any of the information, products or processes included in this publication. The reader is cautioned to carefully review the material presented herein.** Such information must be used together with sound engineering judgment when applied to specific engineering projects. This *Interim Guidelines Advisory* has been prepared by the SAC Joint Venture with funding provided by the Federal Emergency Management Agency, under contract number EMW-95-C-4770. The SAC Joint Venture gratefully acknowledges the support of FEMA and the leadership of Michael Mahoney and Robert Hanson, Project Officer and Technical Advisor, respectively. The SAC Joint Venture also wishes to express its gratitude to the large numbers of engineers, building officials, organizations and firms that provided substantial efforts, materials, and advice and who have contributed significantly to the progress of the Phase 2 effort.

PREFACE

Purpose

The purpose of the *Interim Guidelines Advisory* series is to provide engineers and building officials with timely information and guidance resulting from ongoing problem-focused studies of the seismic behavior of moment-resisting steel frame structures. These advisories are intended to be supplements to *FEMA-267 Interim Guidelines: Evaluation, Repair, Modification and Design of Welded Steel Moment Frame Structures* first published in August 1995.

The first *Interim Guidelines Advisory, FEMA-267a,* was published in January 1997. The specific revisions and updates to the *Interim Guidelines* contained in *FEMA-267a* were developed based on input obtained from a group of engineers and building officials actively engaged in the use of the *FEMA-267* document, in the period since its initial publication in August 1995. That input was obtained during a workshop held in August 1996, in Los Angeles, California.

This second Interim Guidelines Advisory has been prepared as a series of updates and revisions both to the *FEMA-267, Interim Guidelines* which it supplements and to the *FEMA-267a, Interim Guidelines Advisory* publication, which it supercedes. The material contained in this *Interim Guidelines Advisory No. 2* is based on the extensive analytical and laboratory research that has been conducted by the SAC Joint Venture and other researchers during the intervening period, along with recent developments in the steel construction industry. The material contained in this *Advisory* has been formatted to match that contained in the original *Interim Guidelines,* to permit the user to insert this material directly into appropriate sections of that document. This *Advisory* is not intended to serve as a self-contained text and should not be used as such. It does, however, completely replace the material contained in *FEMA-267a*.

A new set of recommendations for the design, analysis, evaluation repair, retrofit and construction of moment-resisting steel frames is currently being prepared as part of the Phase 2 Program to Reduce Earthquake Hazards in Steel Moment Frame Structures. These new Seismic Design Criteria, which are anticipated to be completed early in the year 2000, will replace in their entirety the *FEMA-267 Interim Guidelines* and this *Interim Guidelines Advisory No. 2.*

Background

The Northridge earthquake of January 17, 1994, dramatically demonstrated that the prequalified, welded beam-to-column moment connection commonly used in the construction of welded steel moment resisting frames (WSMFs) in the period 1965-1994 was much more susceptible to damage than previously thought. The stability of moment frame structures in earthquakes is dependent on the capacity of the beam-column connection to remain intact and to resist tendencies of the beams and columns to rotate with respect to each other under the influence of lateral deflection of the structure. The prequalified connections were believed to be ductile and capable of withstanding the repeated cycles of large inelastic deformation explicitly relied upon in the building code provisions for the design of these structures. Although many affected connections were not damaged, a wide spectrum of unexpected brittle connection

fractures did occur, ranging from isolated fractures through or adjacent to the welds of beam flanges to columns, to large fractures extending across the full depth of the columns. At the time this damage was discovered, the structural steel industry and engineering profession had little understanding of the specific causes of this damage, the implications of this damage for building safety, or even if reliable methods existed to repair the damage which had been discovered. Although the connection failures did not result in any casualties or collapses, and many WSMF buildings were not damaged, the incidence of damage was sufficiently pervasive in regions of strong ground motion to cause wide-spread concern by structural engineers and building officials with regard to the safety of these structures in future earthquakes.

In response to these concerns, the Federal Emergency Management Agency (FEMA) entered into a cooperative agreement with the SAC Joint Venture to perform problem-focused study of the seismic performance of welded steel moment connections and to develop interim recommendations for professional practice. Specifically, these recommendations were intended to address the inspection of earthquake affected buildings to determine if they had sustained significant damage; the repair of damaged buildings; the upgrade of existing buildings to improve their probable future performance; and the design of new structures to provide more reliable seismic performance. Within weeks of receipt of notification of FEMA's intent to enter into this agreement, the SAC Joint Venture published a series of two design advisories (SAC, 1994a; SAC, 1994b). These design advisories presented a series of papers, prepared by engineers and researchers engaged in the investigation of the damaged structures and presenting individual opinions as to the causes of the damage, potential methods of repair, and possible designs for more reliable connections in the future. In February 1995, *Design Advisory No. 3* (SAC, 1995a) was published. This third advisory presented a synthesis of the data presented in the earlier publications, together with the preliminary recommendations developed in an industry workshop, attended by more than 50 practicing engineers, industry representatives and researchers, on methods of inspecting, repairing and designing WSMF structures. At the time this third advisory was published, significant disagreement remained within the industry and the profession as to the specific causes of the damage observed and appropriate methods of repair given that the damage had occurred. Consequently, the preliminary recommendations were presented as a series of issue statements, followed by the consensus opinions of the workshop attendees, where consensus existed, and by majority and dissenting opinions where such consensus could not be formed.

During the first half of 1995, an intensive program of research was conducted to more definitively explore the pertinent issues. This research included literature surveys, data collection on affected structures, statistical evaluation of the collected data, analytical studies of damaged and undamaged buildings and laboratory testing of a series of full-scale beam-column assemblies representing typical pre-Northridge design and construction practice as well as various repair, upgrade and alternative design details. The findings of this research (SAC 1995c, SAC 1995d, SAC 1995e, SAC 1995f, SAC 1995g, SAC 1996) formed the basis for the development of FEMA 267 - *Interim Guidelines: Evaluation, Repair, Modification, and Design of Welded Steel Moment Frame Structures* (SAC, 1995b), which was published in August, 1995. FEMA 267 provided the first definite, albeit interim, recommendations for practice, following the discovery of connection damage in the Northridge earthquake.

As a result of these and supplemental studies conducted by the SAC Joint Venture, as well as independent research conducted by others, it is now known that a large number of factors contributed to the damage sustained by steel frame buildings in the Northridge earthquake. These included:

- design practice that favored the use of relatively few frame bays to resist lateral seismic demands, resulting in much larger member and connection geometries than had previously been tested;
- standard detailing practice which resulted in the development of large inelastic demands at the beam to column connections;
- detailing practice that often resulted in large stress concentrations in the beam-column connection, as well as inherent stress risers and notches in zones of high stress;
- the common use of welding procedures that resulted in deposition of low toughness weld metal in the critical beam flange to column flange joints;
- relatively poor levels of quality control and assurance in the construction process, resulting in welded joints that did not conform to the applicable quality standards;
- excessively weak and flexible column panel zones that resulted in large secondary stresses in the beam flange to column flange joints;
- large variations in the strengths of rolled shape members relative to specified values;
- an inherent inability of material to yield under conditions of high tri-axial restraint such as exist at the center of the beam flange to column flange joints.

With the identification of these factors it was possible for *FEMA 267* to present a recommended methodology for the design and construction of moment-resisting steel frames to provide connections capable of more reliable seismic performance. This methodology included the following recommendations:

- proportion the beam-column connection such that inelastic behavior occurs at a distance remote from the column face, minimizing demands on the highly restrained column material and the welded joints;
- specify weld filler metals with rated toughness values for critical welded joints;
- detail connections to incorporate beam flange continuity plates, to minimize stress concentrations;
- remove backing bars and weld tabs from critical joints to minimize the potential for stress risers and notch effects and also to improve the reliability with which flaws at the weld root can be observed and repaired;

- qualify connection configurations through a program of full-scale inelastic testing of representative beam-column assemblies, fabricated in the same manner as is proposed for use in the structure;

- increased participation of the design professional in the specification and surveillance of welding procedures and the quality assurance process for welded joints.

In the time since the publication of *FEMA-267*, SAC has continued, under funding provided by FEMA, to perform problem-focused study of the performance of moment resisting connections of various configurations. This work, which is generally referred to as the SAC Phase II program, includes detailed analytical evaluations of buildings and connections, parametric studies into the effects on connection performance of connection configuration, base and weld metal strength, toughness and ductility, as well as additional large scale testing of connection assemblies. The intent of this study is to support development of final guidelines that will present more reliable and economical performance-based methods for:

- identification of damaged structures following an earthquake and determination of the extent, severity and consequences of such damage;

- design of effective repairs for damaged structures;

- identification of existing structures that are vulnerable to unacceptable levels of damage in future earthquakes;

- design of structural upgrades for existing vulnerable structures;

- design of new structures that are suitably resistant to earthquake induced damage;

- procedures for construction quality assurance that are consistent with the levels of reliability intended by the design criteria.

This Phase II program of research, which is being conducted by the SAC Joint Venture in parallel and coordination with work by other researchers, is anticipated to be complete in late 1999. It is the intent of FEMA and the SAC Joint Venture to ensure that pertinent information and findings from this program are made available to the user community in a timely manner through the publication of this series of design advisory documents. This *Interim Guidelines Advisory No. 2* is the second such publication.

Format

This *Advisory* has been prepared as a series of updates and revisions to the *FEMA-267, Interim Guidelines* publication. It has been formatted in a manner intended to facilitate the identification of changes to the original *FEMA-267* text. Only those sections of *FEMA-267* that are being revised at this time are included. Other sections of *FEMA-267* remain in effect as the current best recommendations of the SAC Joint Venture. This *Advisory* replaces the earlier *Interim Guidelines Advisory, FEMA-267a*, in its entirety.

To facilitate coordination of this *Advisory* with *FEMA-267*, the existing system of chapter and section numbering has been retained. The Table of Contents lists all sections of the chapters being revised, including those sections for which no revisions are included. Within the body of this document, a section heading is provided for each section of the chapter; however, if no revision to the section is currently being made, this is indicated immediately beneath the section heading.

To facilitate reading of this document, where a revision is made to a section in *FEMA 267*, the entire text of that section is included herein. Where existing text from *FEMA-267* is reproduced in this document, without edit, it is shown in normal face type for guidelines, and in italicized type for commentary. Where existing text is being deleted, this is shown in strike through format. A single strikethrough indicates text deleted in the first advisory, *FEMA-267a*. A double strikethrough indicates text deleted in this current advisory. New text is shown in underline format. A single underline identifies text added in the first advisory, *FEMA-267a*. A double underline identifies text added in this current advisory. When a modification has been made to a portion of text, relative to *FEMA-267*, this will also be noted by the presence of a vertical line at the outside margin of the page. The following two paragraphs illustrate these conventions for guideline and commentary text, respectively.

> This sentence is representative of typical guideline text, that has been reprinted from FEMA-267 without change.~~This sentence, is representative of the way in which text being deleted from FEMA-267 in this *Interim Guidelines Advisory* is identified.~~ ~~This sentence illustrates the way in which text deleted from FEMA-267 in the previous *Interim Guidelines Advisory* is identified.~~ This sentence illustrates the way in which text being added to *FEMA-267* in this *Interim Guidelines Advisory* is identified.This sentence illustrates the way in which text added to FEMA-267 in the previous *Interim Guidelines Advisory* is identified.
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> *Commentary: This sentence is representative of typical commentary text, that has been reprinted from FEMA-267 without change.~~This sentence is representative of the way in which commentary text being deleted from FEMA-267 in this Interim Guidelines Advisory is identified.~~ ~~However, this sentence, is representative of the way in which text being deleted from FEMA-267 commentary in the previous Advisory is identified.~~ This sentence indicates the way in which text added to the FEMA-267 commentary in this Advisory is shown.This final sentence illustrates the way in which text added in previous advisory, FEMA-267a, is identified.*

Intent

This *Interim Guidelines Advisory*, together with the *Interim Guidelines* they modify, are primarily intended for two different groups of potential users:

a) Engineers engaged in evaluation, repair, and upgrade of existing WSMF buildings and in the design of new WSMF buildings incorporating either Special Moment-Resisting Frames or Ordinary Moment-Resisting Frames utilizing welded beam-column connections. The

recommendations for new construction are applicable to all WSMF construction expected to resist earthquake demands through plastic behavior.

b) Regulators and building departments responsible for control of the evaluation, repair, and occupancy of WSMF buildings that have been subjected to strong ground motion and for regulation of the design, construction, and inspection of new WSMF buildings.

The fundamental goal of the information presented in the *Interim Guidelines* as modified by this *Advisory* is to help identify and reduce the risks associated with earthquake-induced fractures in WSMF buildings through provision of timely information on how to inspect existing buildings for damage, repair damage if found, upgrade existing buildings and design new buildings. The information presented here primarily addresses the issue of beam-to-column connection integrity under the severe inelastic demands that can be produced by building response to strong ground motion. Users are referred to the applicable provisions of the locally prevailing building code for information with regard to other aspects of building construction and earthquake damage control.

Limitations

The information presented in this *Interim Guidelines Advisory*, together with that contained in the *Interim Guidelines* it modifies, is based on limited research conducted since the Northridge Earthquake, review of past research and the considerable experience and judgment of the professionals engaged by SAC to prepare and review this document. Additional research on such topics as the effect of floor slabs on frame behavior, the effect of weld metal and base metal toughness, the efficacy of various beam-column connection details and the validity of current standard testing protocols for prediction of earthquake performance of structures is continuing as part of the Phase 2 program and is expected to provide important information not available at the time this *Advisory* was formulated. Therefore, many of the recommendations cited herein may change as a result of forthcoming research results.

The recommendations presented herein represent the group consensus of the committee of Guideline Writers retained by SAC following independent review by the Project Oversight Committee. They may not reflect the individual opinions of any single participant. They do not necessarily represent the opinions of the SAC Joint Venture, the Joint Venture partners, or the sponsoring agencies. Users are cautioned that available information on the nature of the WSMF problem is in a rapid stage of development and any information presented herein must be used with caution and sound engineering judgment.

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