TECHNICAL EVALUATION REPORT

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EVALUATION OF WATTS BAR UNITS 1 AND 2 CABLE PULLING AND CABLE BEND RADII CONCERNS

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Prepared for

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FOREWORD

This Technical Evaluation Report was prepared by Franklin Research Center under a contract with the U.S. Nuclear Regulatory Commission (Office of Nuclear Reactor Regulation, Division of PWR Licensing-A) for technical assistance in support of NRC operating reactor licensing actions. The technical evaluation was conducted in accordance with criteria established by the NRC.

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1. INTRODUCTION

1.1 BACKGROUND

The Tennessee Valley Authority (TVA) and Region II of the U.S. Nuclear Regulatory Commission (NRC) received reports of numerous concerns from TVA employees and contractors relating to the adequacy of construction practices at Watts Bar Nuclear Plant. To handle these reports, TVA hired a contractor to collect and document the concerns while maintaining the confidentiality of the concerned individual. The resulting concerns were forwarded to the NRC for review by TVA. Under contract to the NRC, Franklin Research Center (FRC) reviewed and organized the concerns. The review revealed that a significant number of concerns centered on potential damage to electrical cables from deficient cable pulling techniques and from bending cables to less than the minimum bend radii recommended by the cable manufacturers and by industry standards.

1.2 PURPOSE OF FRC'S EVALUATION

To determine if significant cable abuse had occurred during installation, the NRC requested FRC to assemble a team of cable manufacturing and installation experts. The team was charged with:

- o determining if significant differences exist between accepted industry practices and those employed at the Watts Bar plant
- o determining the extent that TVA cable installation procedures were in accordance with cable practices and standards at the time of cable installation
- o discussing cable pulling and bend radii concerns with TVA engineering and installation personnel
- o performing plant walkdowns to attain a general impression of the quality of the cable system installation
- o providing a Technical Evaluation Report (TER) describing the scope and nature of significant cable installation problems.

1.3 FRC'S APPROACH AND CHRONOLOGY OF THE EVALUATION

The team's evaluation concentrated on the pulling of cables into and through conduits, and on temporary and permanent bend radii of the cables. In addition to reviewing written information provided by TVA, a meeting was held at TVA engineering headquarters in Knoxville, TN, on July 17, 1986, to discuss sidewall bearing pressure and other cable pulling concerns. Prior to the July 17, 1986 meeting, TVA provided the FRC team with copies of the report [1]* from their cable sidewall bearing pressure test program as a basis for discussion during the meeting. Two site audits were also performed, one on July 18, 1986 and a second on September 9 and 10, 1986. During both site audits, conversations were held with electricians who had installed cables under present procedures and under the procedures in effect during the 1978-1983 period when the bulk of the cables were installed. After the first site visit, TVA provided isometric drawings and further information relating to the conduits that TVA had determined to have the 82 worst-case cable pulls. After this new information was reviewed by the FRC team, the second site visit was deemed necessary.

Following the meetings with TVA on July 17 and 18, 1986, FRC prepared a formal request for additional information that was forwarded to TVA by the NRC on August 4, 1986. TVA formally responded to this request for information on October 7, 1986 [2].

1.4 DESCRIPTION OF REPORT CONTENTS

Section 2 of this TER provides a summary of the employee concerns that were the impetus for evaluating cable pulling and bend radii at the Watts Bar plant. Section 3 is an evaluation of the adequacy of TVA specifications and procedures for cable and conduit installation with respect to practices in the cable industry. Section 4 discusses cable pulling practices as they were described by TVA electricians and engineers who were involved with the work. Sections 5 through 10 describe technical issues that were found to be significant during the evaluation. Section 11 describes observations made during audits of the Watts Bar conduit system. Section 12 describes the potential effects of the types of cable abuse that occurred at the Watts Bar plant. Section 13 describes TVA's proposed equipment failure trending program that will include cables. Section 14 presents the conclusions of the evaluation, and Section 15 provides recommendations for further action by TVA.

*Bracketed numbers refer to the references listed in Section 16.

Section 3.2.1.2 then states that the maximum "force" on a cable shall not exceed factors of 100 or 30C (depending on the cable type) times the specified bend radius in feet. In the absence of any reference to limiting tension to control sidewall bearing pressure (SWBP) during cable installation, this second limit can only be taken as an alternate type of tension limit, which is wrong and would give improper guidance. Further error and confusion follows in Section 3.2.1.2d where the use of the 100 or 300 factors is said to be an "alternate" to the use of a table of tension limits that are based upon the 0.008 x circular mils rule. Sidewall bearing pressure is never mentioned or dealt with as such. Apparently, the writer and approvers of the standard were not familar with the fact that the 0.008 x circular mils limit and the 100 or 300 x the bend radius limit must be satisfied simultaneously.

G-38 R8 incorporates more cable pulling requirements than G-38 R-2, but still contains errors and omissions of concern. An ambiguity exists in Section 3.2.1.6.1 in which five cases where SWBP is not required to be calculated are described. Nevertheless, Section 3.2.1.6.1.c appears to require the calculation of SWBP. The note under Section 3.2.1.6.1.e concerning SWBP calculation is in error in that it overlooks the distinct possibility that different conduit bends in a run may have different radii.

Section 3.2.1.6.2 of G-38 R8 requires use of a 0.3 coefficient of friction, which is too low for many of the cable and lubricant combinations used at the Watts Bar plant. The 0.5 coefficient required for use in evaluating pullbys and pullbacks is also very nonconservative for cable and lubricant combinations used at the Watts Bar plant.

Detailed trigonometric formulas required by Section 3.2.1.6.2 for the effect of cable weight through vertical bends contribute to the formidable appearance of the calculation, but represented a meager refinement in the result since the values assumed for the coefficients of friction are nonconservative and accurate to only one significant figure or less. The example calculation in Appendix D to G-38 R8 illustrates the point and shows that the complex trigonometric portion of the calculation represents a change of less than 1% to the calculated tension. Repetition of pages of calculational material in Section 3.2.1.6.3 from 3.2.1.6.2 for muitiple cable pulls makes specification G-38 R8 appear technically strong but detracts from its practical usefulness.

3. EVALUATION OF TVA SPECIFICATIONS AND PROCEDURES

3.1 GENERAL STATUS OF CABLE INSTALLATION PRACTICES AVAILABLE FROM THE CABLE INDUSTRY

A primary issue in the evaluation of the cable installation concerns relating to Watts Bar Units 1 and 2 is the extent to which TVA's cable installing procedures conformed to industry standards throughout the period of cable installation. In performing this evaluation, the evaluators arrived at the heightened awareness that no definitive source exists that contains a complete description of standard utility-industry practices for cable installation. The nature of cable conduit installations is such that the cables terminate in a limited number of types of relatively controlled configurations (e.g., control and termination cabinets, motor control centers, and circuit breakers). However, the configurations of cable conduit runs are extremely variable with large variations in the geometry, location, and accessibility of pull points, and in the environments to which the conduits are exposed. Certain rules of thumb have been agreed upon in the cable industry, usually containing broad margins of safety to accommodate the inevitable adverse factors that frequently affect cable installation (e.g., adverse conduit configurations, awkward pull points, and insufficient lubrication).

Because the guidance available from the cable supply industry is general and not application-specific, major users or designers of cable systems usually develop their own in-house installation rules or standards to meet their particular needs by drawing on the recommendations of manufacturers specializing in utility type cables. They also rely upon experts to make design or on-the-spot construction decisions based upon their knowledge of cable structures and potential modes of cable failure. The experts may be from their own staff, from an engineering firm, or from the major cable suppliers.

In addition to the cable bending radius guidelines given in some ICEA publications, IEEE Stds 422 and 690 contain some important cable installation guidelines for generating stations and nuclear stations, respectively. However, there are many installation elements not covered by these documents. Such sources as technical papers, panel discussions, and manufacturers' engineering information have dealt with most of the elements not covered by the standards and constitute the knowledge available to those involved in the cable installation work. These sources form the basis of the term "industry practice" as used in this report. For the nuclear construction industry, the only unique aspect of installation practice to prevent cable abuse and damage is to apply all general guidelines with added conservatism.

Today, there is a definite awareness in the cable engineering community that the utilities industry's published guidance for cable installation is incomplete, and initial steps are being taken to fill some gaps in specific areas relating to cable installation abuse. The task is difficult because of the complexity of evolving cable materials and designs and the variety of installation conditions in practice. Unfortunately, those persons most aware of the inadequacy of the standards are also those most knowledgeable and informed about proper cable installation practices and, thus, personally have not felt the need for producing more detailed, up-to-date standards. Until such standards are produced jointly by users, designers, and manufacturers, there will be continued concern that abuse has occurred during installation as judged by various experts each having their own obviously different biases and opinions.

The following subsections relating to TVA Watts Bar cable installation specifications and procedures must be considered in light of the above discussion. Those aspects of cable installation practice which would clearly be agreed upon by a majority of cable installation experts have been addressed.

3.2 TVA SPECIFICATIONS AND PROCEDURES

The following is a list of the TVA procedures, standards, and specifications that were reviewed in the evaluation of Watts Bar cable pulling and bend radii concerns. The revisions of these documents that were in effect during the period when the bulk of the cable installation was performed (1978-1983) and the present revision were reviewed.

TVA No.	Title	Revision(s) Reviewed
G-38	General Construction Specification for Installing Insulated Cables Rated Up to 15,000 Volts	R2, 8/3/78; R8, 3/17/86
G-40	General Construction Specification for Installing Electrical Conduit Systems and Conduit Boxes	R2, 1/10/79 R9, 5/22/86

TVA No.	Title	Revision(s) Reviewed
DS E 12.1.5	Electrical Design Standard for Minimum Radius for Field Installed Insulated Cables Rated 15 kV and Less	R0, 9/20/83, R1, 4/23/86
DS E 13.1.4	Electrical Design Standard for Maximum Cable Diameters for Various Rigid Steel Conduits	R1, 8/24/83
DS E 13.1.7	Electrical Design Standard for Dimensions of Rigid and Flexible Metal Conduit Bends	R1, 9/26/83
DS E 13.6.2	Electrical Design Standard for Use of Conduit Bodies in Conduit Systems	R1, 4/17/86
QCI 3.05	Watts Bar Nuclear Plant Quality Control Instruction for Cable Installation	R0, 7/19/82; R10, 11/26/85
QCP 3.05	Watts Bar Nuclear Plant Quality Control Procedure for Installation, Inspection, and Testing of Installed Control, Signal and Power Cables	R7, 1/29/79; R26, 4/25/86
MAI-3	Watts Bar Nuclear Plant, Modifications and Additions Instruction for Installation and Inspection of Insulated Control, Signal and Power Cables, Units 1 and 2	R6, 1/15/86
MAI-4	Watts Bar Nuclear Plant, Modifications and Additions Instruction for Installation and Inspection of Cable Terminations	R4, 6/27/86
MAI-13	Watts Bar Nuclear Plant, Modifications and Additions Instruction for Installation of Conduit and Junction Boxes	R3, 9/5/86

At the Watts Bar plant, the bulk of the cables were installed between 1978 and 1983. Therefore, the evaluation of the procedures and practices concentrated on documents in effect during this period and documents in effect today. The primary source of installation instructions from August 1978 through September 1982 was Revision 2 of General Construction Specification G-38 (G-38 R2) [3]. The present revision of this specification is Revision 8 [4] dated March 17, 1986.

The aspects of cable installation where TVA specifications lacked guidance or differed markedly from industry practices in 1978 and 1986 are pulling tension, sidewall bearing pressure, bending radii, support of vertical cable, pullbys, pulling attachments, splice and repair locations, and cable jamming dangers.

When reviewing these specifications individually or considering them collectively, it was unclear to whom they were addressed and just which documents would be used in the field by electricians, foremen, construction engineers, or designers. Much partial duplication, mixing of practical how-to's with complex trigonometric formulas, and references to other documents made it difficult to imagine how any worker could have used the specifications and procedures effectively. Enclosure 2 of Reference 2 provided some insight into the use of the specifications and procedures. Specification G-38 is the overall TVA corporate specification for cable installation. At the Watts Bar plant, Quality Control Instructions (QCIs) and Quality Control Procedures (QCPs) provided guidance from G-38 for construction craft use. TVA stated in Enclosure 2 to Reference 2 that craft training modules were developed from information contained in the QCIs and QCPs. When systems were turned over to the operating group, further modification responsibilities were transferred from the construction department to the modifications department. Modifications to the cable system are governed by Modification and Addition Instructions (MAIs) such as MAI-3 [5] for cable installation, MAI-4 [6] for cable termination, and MAI-13 [7] conduit and junction box installation. MAIs 3 and 13 include much of the information from G-38 and G-40, but are organized simply as a long set of sections and attachments without benefit of a table of contents. Review of these MAIs indicates that they are not easy to use.

3.3 TECHNICAL ISSUES

3.3.1 Pulling Tension Related to Stretching and Sidewall Bearing Pressure

Confusing terms and conflicting requirements are given in Section 3.2.1.2 of G-38 R2. The term "force" is used repeatedly in place of "tension" in the text. In citing the commonly used tension formula, 0.008 lb/circular mil x the area of the conductor in circular mils,* the term "force" is used.

*A circular mil is used to define cross-sectional areas of cables and is a unit of area equal to the area of a circle 0.001 inches in diameter.

Section 3.2.1.2 then states that the maximum "force" on a cable shall not exceed factors of 100 or 300 (depending on the cable type) times the specified bend radius in feet. In the absence of any reference to limiting tension to control sidewall bearing pressure (SWBP) during cable installation, this second limit can only be taken as an alternate type of tension limit, which is wrong and would give improper guidance. Further error and confusion follows in Section 3.2.1.2d where the use of the 100 or 300 factors is said to be an "alternate" to the use of a table of tension limits that are based upon the 0.008 x circular mils rule. Sidewall bearing pressure is never mentioned or dealt with as such. Apparently, the writer and approvers of the standard were not familar with the fact that the 0.008 x circular mils limit and the 100 or 300 x the bend radius limit must be satisfied simultaneously.

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In regard to controlling the tension during a pull, Section 3.2.1.7 uses the term "monitor" in the unusual and misleading senses of either to measure or to simply limit the tension. Either sense of the term is applicable anywhere in the TVA cable pulling practices, but the implied benefits of measuring are assumed when, in fact, there is no assurance that any measurement is done. In the total absence of guidelines on use of mechanical pullers and on methods of attaching pull ropes to cables after the cables first emerge from pull points, any confusion or sloppiness in defining "monitoring" and how and when it is to be used can lead to undetected cable abuse.

Section 3.2.1.7.1 of G-38 R8 contains an unfortunate error which is also contained in the figures on page 3-18; it describes the tension limit as F_m (from the 0.008 x circular mils rule), but ignores the tension limits from SWBP calculations.

TVA specification G-40 R2 provides no guidance aimed at limiting pulling tensions or sidewall bearing pressure at bends through proper design and installation of the conduit system.

The current revision, G-40 R9, does contain some guidance related to prevention of cable abuse in that it limits the total of bends in a pull to 360° and cautions that condulets must be sized to "accommodate" the cable. There is evidently no consideration given to coordinating the orientation of condulets with the actual direction in which cables will be pulled. Both revisions of G-40 also allow substitution of 90° condulets for 90° conduit bends, creating many unnecessary pull points. This latter situation noted in the Watts Bar site visits gives rise to the concern that installers may have pulled through a number of 90° condulets with consequent high risks of cable damage. None of the revisions of G-38 contains a specific prohibition against pulling through 90° condulets.

MAI-13 reiterates much of the information in G-38 but adds that pull boxes should be installed in runs over 50 feet long with 180° of bends or in runs over 150 feet with 90° of bends. Those requirements are extremely restrictive when compared to industry practice and may, if used, result in added cable abuse when cables are pulled in, out of, or through these extra boxes rather than through conduit or conduit bends. The extra handling at these pull points could result in additional twisting, tangling, bending, and kinking that need not occur with fewer pull points.

In summary, with respect to pulling tensions, the TVA 1979 standards were very inadequate with regard to SWBP and the use of 90° condulets when compared to industry practice. The current TVA standards (G-38 R8, QCP 3.05 R26, and MAIs-3 R6, -4 R4, and -13 R3) fill most gaps concerning tensional SWBP, but contain assumptions, errors, omissions, repetitions, and mixtures of practical information with theory that give rise to continuing concerns as to whether the use of even these current standards for cable pulling will result in cables that are free from abuse.

3.3.2 Bending Radius

G-38 R2 provides no guidance on permanent bending radius as such. A table with recommended and minimum bending radius factors is contained in Section 3.2.1.2c on pulling forces, but there is no indication that it is applicable to other than conduit bends for tension concerns. Section 2.2.6 on cable bending equipment contains an instruction to follow the manufacturer's instructions, but presumably this refers to the manufacturer of the bending equipment, not the manufacturer of the cable.

TVA standard DS E12.1.5, R1 provides guidance for minimum bends of non-shielded multiconductor cables, but departs from industry practice in using factors of multiples of the outside diameter of largest internal conductor rather than the outside diameter of the overall cable. Another nonconservative guideline differing from any industry practice known to the FRC team is the permitted removal of the jackets of single conductor cable or of those of the individual conductors of multiconductor cable to facilitate making sharper bends. The potential for damaging the cable during such stripping appears to far exceed the risks in overbending the jacketed single or multiconductor cable.

Section 3.2.1.3.4 of G-38 R8 deals with overbending during installation and handling. In effect, it states that if overbending is done during installation, "restore the cable to acceptable radius." There are no explicit, published standards for temporary bends, but there is implied relief for medium voltage cables through published shipping-reel diameter tables contained in ICEA/NEMA cable standards. These published tables imply considerable relief for medium voltage cables but little for low voltage cables. Temporary overbending is a recognized common problem, but there is no utility- or industry-wide consensus on how to address it in a definitive way. TVA's manner of dealing with the temporary bending is probably no better or worse than most other utilities.

TVA standard DS E-13.6.2, R1 addresses special bending problems of medium voltage shielded cables that occurred at the Watts Bar plant; these problems apparently are still in the process of being resolved by TVA. MA1-13 R6, Section 5.6.h instructs electricians to avoid reversing the bend of cables as wound on the reel, when possible. This instruction, which is particularly appropriate to very special situations relating to large, stiff, high voltage cables, is impractical for other general cable installations.

The memorandum from W. S. Raughley dated September 2, 1986 [8] addresses the bend radii problem for medium voltage cable as well as coax type cables, showing an awareness of this issue on the part of TVA and an intent to rectify the attendant problems.

In summary, early TVA standards had far less guidance relating to permanent cable bends than was common in the industry at the time as evidenced by ICEA standards and manufacturers' information then available. Current TVA standards do address key issues, but unnecessary complexities and nonconservative elements give some cause for continued concern.

3.3.3 Vertical Support of Cable in Conduits

G-38 R2 gives guidance for vertical tray cable support, but provides no information for vertical conduits or on the dangers of using 90° condulets at or near the tops of runs. G-40 R2 contains no mention of vertical support of cables in conduits.

Section 3.2.1.9 of G-38 R8 states that cables in vertical conduits shall be supported in accordance with National Electrical Code (NEC) article 300-19 but does not describe the NEC requirement. Section 3.2.1.9 then describes the allowable supporting devices such as Kellems support grips and cast sealant. For supporting cable in conduit bodies (condulets), application of Raychem NJRS nuclear jacket-repair wraparound sleeves is allowed. However, it is not clear how the Raychem sleeves provide support of the cable in the vertical run, nor is it certain that the manufacturer intends the sleeves to be used in such an application. Section 3.2.1.9 does not provide a warning that the predominant cause of cable damage from a 90° conduit located at or near the top of a vertical conduit is from indentation and cutting of the jacket and insulation by the sharp radius at the inside corner of most 90° condulets.

The current G-40 R9 specification gives preference to conduit bends at the top of vertical runs rather than use of 90° condulets and demands "provision for support" if 90° condulets are used. Again, concern seems only to be related to the overall bend radius of the cable rather than the indentation of the jacket and insulation by the corner of a 90° condulet. DS E-13.6.2 1986, "Use of Conduit Bodies," has no reference whatever to vertical support issues. MAI-3 R6 details the NEC-based guidelines and the use of G-38 R8 information and adds the statement that installations with long vertical runs are to have junction boxes at the top with support devices for the cables.

The memorandum from W. S. Raughley dated July 16, 1986 [9] addresses vertical support concerns, but still ignores the danger of indentation and cutting of the cable jacket and insulation at the corner of 90° condulets used near the top of vertical runs. The need for added precautions appropriate to harsh (high temperature) environment areas is not recognized. High temperature increases the probability for indentation and cutting of cable jackets and insulation at the corners of 90° condulets.

In summary, 1978 time-frame TVA specifications and procedures had no guidance for support of cables in vertical conduits. While current documents recognize some aspects of 90° condulet danger near the top of vertical runs, only the current MAI-3 deals with it at a level equivalent to present utility and industrial standard practice. Again, industry standards are far from detailed and complete, but guidance concerning good cable support practices is readily available from cable manufacturers.

3.3.4 Pullbys

A pullby is the pulling of one or more new cables past cables that are already in a conduit. In a pullby, the cable being pulled into the conduit will tend to ride across the existing cables at bends in the conduit. The moving cable and pull rope have a tendency to saw through the stationary cable if friction and pressures are high. G-38 R2 did not address pullbys.

G-38 R8, Section 3.2.1.2 does address the subject and suggests avoiding pullbys where practical, but still allows them. It notes that precautions may be required to avoid damage from SWBP during a pullby. However, SWBP is not the prime cause of damage from pullbys; sawing and cutting of the stationary cable by the moving cable or rope is. Guidance provided in G-38 R8 does cover added friction, the use of more lubricant, a requirement to avoid damage from the pull rope, and stopping the pull if tension suddenly increases; however, no specific methodology or criteria are given. All of these items do reflect current industry concerns, but the large number of pullbys at the Watts Bar plant, together with many plastic jacketed cables mixed with rubber jacketed cables, the complexity of many pulls, and the vagueness of precautions, lead to the conclusion that the Watts Bar pullby problems were frequent and significant and the "solutions" in the current TVA standards less effective than the practices used by most of the utility industry for station construction.

3.3.5 Pulling Attachments

The earlier G-38 R2 contains good detail on methods of fastening cables to pull ropes but does not call for use of the swivels. The use of swivels was introduced in G-38 R4, in 1984.

The current G-38 R8, Section 3.2.1.7.3e indicates basket-weave grips may be used to pull cables out of conduits for reuse. Another section instructs electricians to discard extra cable near pulling grips, which may have been damaged during pulling. These instructions appear to be inconsistent, and the reuse of cable that requires application of grips to pull the cable back to an intermediate pull point would not be in accord, with TVA or industry practice of scrapping cable that was under pulling grips during a pull. During the process of pulling the cable back out of the conduit, the basket-weave grip may damage the insulation, but the current TVA standards ignore this possibility and allow reuse of the cable.

Absent from all TVA standards reviewed is any guidance on how one attaches pull rope to cables at mid-run pull points to pull the balance of cable after the pulling line has emerged. (On-site personnel mentioned using a "rope with half hitches," a practice that can cause significant damage to the insulation during pulling.)

3.3.6 Splice and Repair Location

The earlier G-38 R2, Section 3.4 limits the location of splices to cable trays and junction boxes but does not note any location limits for jacket repairs. Presumably cables with repaired jackets could have been pulled into the conduits.

The current G-38 R-8, Section 3.7 gives a new limitation of no repairs in medium voltage cable except for the jacket, but it allows splicing as an option for other cables, with no limits as to location or whether it is 1E or non-1E cable. Low voltage cables have no restrictions on repair or splice location. Sections 3.4.2 to 3.4.7 on splicing also have no location constraints for splices.

Unless SD E12.5.9, referenced in G-38 R8, but not provided to FRC, has limitations, there appears to be little guidance limiting the location or protection of repairs or splices, which is at odds with most cable and splicing material manufacturers' specifications.

3.3.7 Jamming Danger

Neither G-38 R2 or R8, nor any other TVA standard reviewed, indicates any awareness of dangers of jamming when three or four cables are installed in a duct or conduit (see Section 7 of this report for a further discussion of jamming). Jamming has been recognized as an industry concern for decades and appears in most manufacturers' installation guides or in standards such as IEEE Std 690-84. The reason for the jamming concern is that while industry practice (including TVA) limits conduit filling to 40%, for three single-conductor cables, the range of 31% to 38% filling is the range in which jamming danger exists. "Efficient" choice of conduit size thus invites the danger of jamming.

4. EVALUATION OF CABLE PULLING PRACTICES

4.1 CABLE PULLING PRACTICES

As a result of dicussions with engineers and electrical workers at the Watts Bar plant, it is known that the bulk of the cables were installed in the following manner:

a. Engineers prepared work orders for the pulls that included such information as termination points, conduit size, number and size of cables, and other basic essentials for the cable run.

b. Electrical workers installed the conduit between the cable termination points specified by the work order. They had latitude in locating the conduit and in choosing and locating the conduit components such as condulets.

c. Usually another crew of electrical workers did the actual cable pulling after the conduit system was in place. This crew had the choice of the direction of pull and of the number of pull points that were actually used. Some pulls points may have been attained by disassembling the conduit and reassembling it after the pull was completed. However, this practice was not documented.

d. If problems arose during the pull, engineering and quality control groups were called in to evaluate and resolve the situation.

This manner of installation indicates that the bulk of the pulls were made without the work really being engineered. Actual tension, sidewall bearing pressure forces, and bending radii were not known at the time of the pulls and cannot be established at this late date. As a consequence, it is not possible to state definitely whether the bulk of the cables were properly installed.

It became obvious during the discussions with TVA personnel that most of the burden for quality depended on the skill of the workmen. The electricians that were interviewed displayed a good attitude and knowledge of the field requirements for proper installation.

4.2 CONTROL OF TENSION

Tension "control" or "monitoring" under TVA specifications and procedures means use of either a dynamometer or break link, or simply detecting changes in tension of the pull rope when pulling by hand. Discussion with installers at the site indicated break links were almost universally used on mechanically assisted pulls. The 1979 through 1986 versions of QCP and QCI 3.05 give adequate information on the testing, selection, and use of break links or break lines based upon the 0.008 x circular mil rule for cable stretching. The current specifications such as G-38 R8 now deal with SWBP limitations. However, the awareness and concern shown by electricians responsible for cable installation, together with FRC's inspection of cable ends at the plant and the inherent margin of safety of the cables to SWBP, leads to the belief that there are very few cables in place likely to have suffered significant crushing damage from tension around conduit bends (SWBP).

There are voids in the TVA installation instructions which cause concern for cable damage during pulling beyond those that straightforward stretching or SWBP calculations would reveal. One of these is the methods used to apply tension to a midpoint on a cable during a pull. For long mechanically assisted pulls with many pull points, the pulling of cable beyond that point where the pulling rope emerges presents a field problem relating to providing a gripping method for midcable pulling that will not damage the cable. Instructions for pullbacks now specify the use of mesh grips. Use of such grips requires considerable care to prevent tearing and cutting damage to the jacket and insulation. Installers mentioned the use of a rope and half hitches for midpoint pulling, a practice that could damage the cable. With either basket grips or half hitches, and with tensions even a fraction of the 0.008 x circular mil rule limits, serious damage could result to the cable that ultimately will be located in the conduits and will be unobservable. The lack of detail on the mechanical devices used and the handling of the cable when it was pulled out of and into the numerous intermediate pull points leaves a great deal of uncontrolled latitude to the installers. The difficulty of preventing multicable crossovers, kinks, and twists in pull point loops and of preventing high tension in some conductors going through 90° condulets with their sharp corners is felt to be as much or greater than the risks resulting from pulling tensions that give rise to excessive SWBP. The experience of installers and the encouragement by construction management to the installers to take pains to minimize these damage risks become major factors that are not truly assessable after completion of cable installation.

4.3 USE OF MID-CONDUIT PULL POINTS

During the discussions with the electricians, the various types of pull points were described. Pull-boxes were usually installed at the direction of the engineering group. Condulets (straight and 90°) were installed at the option of the conduit installer when a pull would exceed 360° of bends or prescribed length limits. If the pull rope broke during a pull and the cable could not be pulled into a conduit, the cable would be removed and a pull point added. In some cases, the conduit was disassembled to make a pull point and then reassembled with the cable in place. The actual use of pull points is not documented. For example, there is no record of whether a straight condulet was used as a pull point or if the cable was pulled straight through it.

During the first discussion with electricians on July 18, 1986, the descriptions of pull point use indicated that the cables were pulled completely out of a pull point and then inserted into the next segment and pulled again. This method led to concerns relating to condulet pull points. When cables are pulled out of a condulet and reinserted into the other side, the last portion of the loop of cable entering the condulet is subjected to very harsh bending. For many cables used at the Watts Bar plant, the bend radius is on the order of three to four times the diameter of the cable. Such a small bend radius exceeds the minimum allowable limit for any of the types of cable used at the Watts Bar plant.

The discussions with the Watts Bar electricians on September 9, 1986 provided further insight into use of pull points. In this discussion, they stated that, most often, cables were not pulled completely out of the condulet. Rather, electricians were stationed at each pull point to "help" the cable along by hand without pulling the cable out of the condulet. If needed, more lubricant was added at a pull point. Communications between electricians was generally by voice and involved yelling to each other through the conduit.

While the first method of pulling raises concern relating to excessive bending damage, the effectiveness of the second method in providing a controlled pull is unclear. Certainly, the difficulty in performing a tension or SWBP calculation for the second method is increased inordinately. The tension carried from one segment of the pull to the next is not independent in the second method of pulling. The ability of the electrician to "help" the cable along is questionable given the awkward location of many of the condulets and the limited space for hand holds in most condulets. If the electrician could truly help the cable along, was there any way in which to judge the pulling tension he was applying? And lastly, it is difficult to envision the simultaneous application of lubricant while helping a cable along in a condulet.

4.4 LUBRICANTS AND LUBRICATION

A variety of cable pulling lubricants have been used at the Watts Bar plant. The bulk of the cables were pulled during the time that Yellow-77 or Y-er Ease was available for plastic and rubber jacketed cable, and dust with mica or soapstone was available for use on cables with braided coverings. At the time of a cable pull, the decision to use lubrication, as well as the amount to use, was left to the electricians.

G-38 R2 provides a list of allowable lubricants but does not provide any guidance for their use. G-38 R2 states that "lubricants should be used...when pulling cable into conduits." Most of the cable runs at the Watts Bar plant are comparatively short; hence, probably most of the pulls were made without the use of any lubricant during the 1970s. The electricians appear to have been astute enough to use lubricants for the longer pulls where the pulling tension and sidewall bearing pressure were critical.

The key problem with lubricants at the Watts Bar plant is not their use or lack of use, but the way that they have been accounted for in subsequent calculations of tension and SWBP. In the calculations performed by TVA for the worst-case cable conduits at the Watts Bar plant, very low coefficients of friction were assumed. The static coefficient of friction is defined in its simplest terms as the factor which, when multipled by the normal force exerted by the cable on the conduit by virtue of its weight and the weight of other cables resting on it, yields the pulling tension required to start the cable or cables in motion. The dynamic coefficient of friction is basically the same except it is the tension required to keep the cable or cables in motion.

The static coefficient of friction is generally somewhat larger than the dynamic value. The importance of this fact is that the lowest tensions are obtained by pulling a cable in one continuous action. This is best accomplished with mechanical equipment such as capstans. Evidence indicates that controlled mechanical pulling was seldom the situation at the Watts Bar plant. Even with mechanical equipment, considerable planning is required to make one continuous pull. For example, one employee concern states that a come-a-long was used to pull the cable. Such a hand-operated, ratchet-driven device would produce a pulsing, stop-start pull having alternating high and low tensional forces as the friction cycled between static and dynamic. There is a high probability that most pulls were made using frequent stopping and starting; hence, the static coefficient is the best value to use in calculations.

Technical papers and reports, such as IEEE 84 T&D 375-2 [10] and EPRI EL-3333 [11], provide values of static and dynamic friction. These data show that, on average, the static coefficient friction is about 10 percent greater than the dynamic. The static values for friction will be used in this discussion because of the starting and stopping type of pulling described above and the slight conservatism that is provided.

When cables are pulled into rigid steel conduit, both the jacket material and the type of lubrication (if any) have a significant effect on the friction value. If no lubricant is used, the static coefficients of friction from 1.4 (for Hypalon) to 0.55 (for polyvinyl chloride) are typical and represent materials actually used. The application of talcum powder to smooth, extruded jackets reduces the values to the range of from 0.42 to 0.62, depending on the jacket material. It should be noted that talcum powder was used only on cables with braided jackets for which no comparative data are available. It is reasonable to expect a slightly higher coefficient of friction would apply for braided cables because much of the lubricant would fall into the voids in the braiding.

A type of lubricant that further reduces the friction is one that is made of bentonite clay and water. Typical values are 0.25 to 0.50 for these jackets in rigid conduits. The lowest values for pulling compounds used prior to the 1980s are obtained with wax emulsion, and values of 0.15 to 0.37 are shown in the literature. These materials were not commonly used at the Watts Bar plant; Yellow 77 was.

The newer Polywater J and similar compounds reduce static friction coefficients to 0.15 to 0.18. This was the material used in TVA's sidewall bearing pressure (SWBP) tests and now used for cable pulling at the Watts Bar plant.

The above information shows that large variations in the coefficients of friction could have existed under the differing conditions that occurred during pulls prior to the use of Polywater J as a lubricant. This is significant in relation to the TVA plants for the following reasons:

1. The means of application, type, and quantity of lubricant actually used in the past pulls are not fully known. The amount of lubricant that actually remained on the cables near the ends of multiple pull points with their "help-along" concept, described in Section 4.3, leaves a question regarding the effectiveness of the lubricant that was used. It is not clear that cables can be adequately lubricated at pull points where they are helped along rather than when they are pulled out and relubricated.

2. Pullbys were made when many cables were already in the conduits. Rather than making use of the coefficients of friction for jacket to steel interfaces, the higher values for the coefficient of friction between the two jacket materials must be used in the calculations.

Back calculations of pulling tensions may require the use of a very conservative coefficient of friction if the facts are not known regarding the actual use or type of lubricant. A value of 0.6 to 0.7 is suggested. For pullbys, an even higher coefficient of friction such as 1.0 should be used.

4.5 PULLING THROUGH FLEXIBLE CONDUITS AND 90° CONDULETS

Sidewall bearing pressure* (SWBP) is the radial force exerted on a cable at a bend when the cable is being pulled around a bend or sheave. Crushing damage to the cable insulation system is the concern. In the United States, the maximum allowable value is usually given in pounds per foot. The definition of SWBP can leave the erroneous impression that only the radius of curvature is involved. Crushing takes place depending on the length of the contact surface. For example, if a cable is supported on a 1/4-inch surface of a 90° condulet while bent to a 1-foot radius, the maximum allowable sidewall bearing pressure is 1/48 of that indicated in the usual tables when only the 1-foot radius is considered. This reduction in allowable force relates to the sidewall force being concentrated on a 1/4-inch surface rather than on the entire bend associated with the 1-foot radius of the cable.

*Note: Pressure is a misnomer in that sidewall bearing pressure is generally given the dimensions of force per unit length of a curved surface.

On the drawings for the worst-case cable conduits at the Watts Bar plant, flexible conduits were shown as being included in many pulls. (Inclusion of flexible conduit in a pull was not part of the evaluation of "worst-case" pulls.) The electricians indicated that, in general, end-of-the-run flexible conduits were not included in a pull. However, some of the conduit runs contained mid-point flexible conduits, indicating that some pulls were made through flexible conduits. The inside surface of a flexible conduit has gaps between the contact areas because of the corrugations. Therefore, the entire surface of the cable running through a bend in a flexible conduit is not supported. A cable under tension that stops moving during a pull will tend to have its surface lock into the corrugations of the bends in a flexible conduit. When movement is resumed by pulling harder on the cable, the shear forces on the cable surface, which are equivalent to very high frictional forces, can severely tear the cable jacket and insulation.

Pulling around a 90° condulet is of greatest concern because the total bearing surface supporting the bend is approximately 1/4 inch long. Considerable damage is likely to occur if cables are pulled under tension around the inside edge of a 90° condulet. The large quantities of 90° condulets used at the Watts Bar plant and the described method of helping cables along at 90° condulets leads to the assumption that some of the cable was actually being supported by the sharp corners of 90° condulets during pulling. For 90° condulets that are likely to have been pulled through, an assessment would be required to determine if damage occurred when the cables were moved under tension over the sharp corner.

5. TENSION AND SIDEWALL BEARING PRESSURE CALCULATIONS

Previous sections of this report have stated that calculations for pulling tension and sidewall bearing pressure at the Watts Bar plant were made many years after the pulls were performed. Many of the crucial facts needed to make an accurate calculation, such as the effectiveness of the lubricants, the use of pull points, and direction of pull, are no longer available.

If these facts were known, reasonably accurate calculations could be performed. Without these facts, many assumptions are needed. An example of this is TVA's assumption for conduit No. 1PLC62E that all of the 15 available pull points were actually used. If only a portion of these available pull points were used, the calculated tension and SWBP values would be much higher than those shown in TVA supporting documents. Another example is conduit No. 1PP 2188A with only one mid-conduit pull point, a straight condulet. If this point was not used, the total bends would be over 750 degrees. If it had been used, the allowable bending radius of the cable would have been greatly exceeded when the final portion of the loop of cable entered the condulet.

As stated in Section 4.4, the choice of 0.3 for the coefficient of friction for cable pulled with Yellow-77 is nonconservative for the calculations. A further complication is the method of manually helping a cable along at a pull point. The method described in Section 4.3 causes an additional concern for the accuracy of the present calculations which assume that the tension in each segment of a conduit is independent of the tension in the next and last segments. Independence cannot be assumed for the help-a-long style of pulling.

The calculations were performed by TVA for the 82 worst-case conduits after the pulling was completed to determine if SWBP and pulling tension limits had been exceeded for the cables. While the assumptions that were used as a basis for these calculations were not fully conservative, the results provided an adequate focus for selection of worst-case conduits for evaluation. However, future calculations performed before pulls are made should entail consideration of higher coefficients of friction, actual pulling points, and the actual direction of the pull.

6. PULLBYS

Pullbys were not recognized in the 1979 version of G-38 (R2) as a subject of concern. In the current specification (G-38 R8), they are permitted but not preferred. Judging from wide separation of cable installation dates shown for some conduits, the "preference" noted in the G-38 R8 specification was often not a field option. The text in the TVA standards and the discussions at the site with engineers and electricians indicate that the preference to avoid pullbys stemmed from concern for the added friction, higher sidewall pressures, possibility of cables jamming during the pull, and the difficulty of getting a pull rope through the conduits. The electricians stated during interviews that examination of cable emerging from the conduit would give assurance that no damage had occurred.

General practice at utilities, as revealed by discussions with utility engineers, recognizes saw-through of the coverings and insulation of in-place cables by the traveling pull rope or cable as the greatest risk in pullbys. It is not necessarily detectable from evaluation of emerging cable, observation of high tension or sudden rises in tension (or jamming), or even by performance of routine electrical tests after installation. Saw-through was recognized by one TVA electrician when he indicated in the on-site discussion, "We had a pull line that came out looking black." Unfortunately, the very abrasive nature of manila or certain braided synthetic pull lines can be severe. The pulling of rubber (thermo-setting) jacketed cables over thermoplastic jacketed/insulated cables maximizes the probability of saw-through damage as the frictional heat and wear are distributed along the cable being pulled but concentrated at particular locations on the in-place cable.

One favorable factor at the Watts Bar plant is that more recent pullbys have used Polywater J as the lubricant. If well applied, it provides a much better chance of the lubricant being effective much further into the conduit than does the earlier used Yellow-77. Yellow-77 tends to wipe off the cable a short way into the conduit.

The net result of the above circumstances is that a realistic assessment of the presence or freedom of damage to cables from pullby saw-through can only be made by removal for examination or by flooding the conduit with water and performing electrical tests. If saw-through damage has occurred and the conduits do become wet due to a harsh environment or condensation, there is danger that common mode failures may occur that could affect multiple systems.

Analysis of the 82 worst-case conduits will indicate those conduits in which the highest amount of pullby damage could have occurred. If the cables from such conduits were electrically tested under wet conditions or removed and examined for damage, conclusions could be drawn concerning whether or not pullby damage is a significant problem for the overall cable system at the Watts Bar plant.

TVA provided information regarding pullbys and harsh environments for the 82 worst-case pulls [2]. Eleven of the conduits having pullbys, indicated through multiple cable pulling dates, also were located in harsh environments. It should also be noted that even in mild environments, wetting of the inside of the conduits is possible due to condensation. One conduit, No. 1PP2188A, examined during the second site visit, was found to be wet. When a vertical condulet was opened, it was found to be filled with water for half of its height. This condition existed under a normal, non-accident environment.

Pullbys, which only recently have been recognized by TVA as being undesirable, have apparently been so judged only because of the added difficulty of the cable pull. The distinct hazard of sawing through the jacket and insulation of the in-place cables has not been realized or addressed by TVA up to the present time.

7. JAM RATIO

When the ratio of the inside diameter of a conduit to the cable diameter is close to 3.0, one of the cables in a three- or four-cable pull may slip between two other cables, causing the cables to jam or wedge in the conduit as the cables are pulled around a bend. The jamming occurs when the summation of the cable diameters approximately matches the conduit diameter. If the summation of the cable diameters is somewhat larger than the conduit diameter, the cables cannot align with each other to cause the jamming. Jamming is most likely to occur when the cables are pulled around a bend rather than when being pulled in a straight run. The ratio of the diameter of the conduit to the diameter of the cable is called the jam ratio.

The limits on jam ratio must recognize variations in cables as well as ovality in the conduit at field bends. The generally recognized formulas are:

$$\frac{D}{d} < 2.8; \ \frac{D}{d} > 3.15$$

where D is the diameter of the conduit and d is the diameter of the cable. One of the above two expressions must be satisfied to remove the concern for jamming.

TVA did not take jam ratio into account during the sizing of the conduit. As described in Section 3, jam ratio is not considered in TVA specifications and procedures. To complicate jamming ratio evaluation, TVA lists cables from several manufacturers as having the same diameter. While some variation is taken into account in the above equations, cables used in runs that are close to being in the jamming region should have their diameters measured individually.

If the cables actually do jam, the tension can increase by a factor of 10. This sudden increase probably would be noticed by the cable pulling crews. Of greater concern is the pull that just begins to jam. In this case, the tension may increase modestly and not be noticed by the installers. Damage to the cable can therefore be more subtle because of crushing or high forces around bends. It is of greater concern to the safety of the plant because the cables and conduits in redundant trains are likely to have the same dimensional factors and similar conduit runs. Therefore, redundant systems could have experienced like cable damage.

If records indicate that pulls were made where the cables and conduit ratios are close to the above limits, actual field measurements of cable and conduit dimensions should be made to determine whether jamming is of concern. If calculation of the jamming ratios indicates that the potential for jamming exists, the worst cases for jamming should be investigated to assess the general level of risk to the plant cable system.

8. CABLE SIDEWALL BEARING PRESSURE TESTS

The TVA test program for sidewall bearing pressure (SWBP), performed in April and May 1986, and its report [1] dated May 1986 represented ideal conditions and may have little direct applicability to the cables pulled during Watts Bar construction. Both situational and technical factors lead to this conclusion.

The situational differences between the station conditions and those simulated by the test are:

1. The method of applying lubricant and the probable effectiveness are totally different. The special flooding device, "Soaper," used in the test was not available for field installations and, more often than not, could not have been used because of the very difficult accessibility of cable feed and pull points during installation.

2. The Polywater lubricant specified for the test was not available at the time of most of the cable installation and is far superior to the lubricants that were actually used. The superiority involves both the low coefficient of friction attained and its resistance to being wiped off the cable surface during pulling. This superiority is significant because damage to cables from severe drag forces is much more common than from radial (SWBP) pressure alone.

3. There is no indication that the test conduits were thoroughly cleaned of lubricant between tests. Therefore, lubricant from prior test pulls probably was present in subsequent tasts and made lubrication nearly perfect for the tests -- far different than pulling into virgin dry conduits s occurred at the Watts Bar plant site.

4. Careful monitoring of cable tensions as performed during the tests was seldom done at the Watts Bar plant and apparently was never recorded in the field. Therefore, neither the magnitude nor instability of tensions can be compared between the tests and the actual installations. Note that "monitor" is used in a quantitative (measurement) sense, not that of TVA standards where it implies only that some means is used to limit the tension.

5. Multicable pulls with cables of mixed sizes and construction as commonly found at the Watts Bar plant were not included in the tests.

6. The pulling source of the test was especially engineered to provide as smooth (continuous) a tension as possible, which is in stark contrast to the field where such methods were apparently seldom, if ever, used.

7. Pullbys, recognized by the industry and by TVA in its recent change to G-38 as potentially damaging to in-place cables, were not evaluated or considered in the scope of the tests.

8. Swivels used during the tests were apparently not commonly used at the Watts Bar plant. There were no requirements for use of swivels and no requirement to record the use of swivels when they were used.

9. The mixing up, twisting, and crossing of cables fed in and out of many successive condulets or pull boxes, as probably occurred in Watts Bar cable pulls, was not evaluated during the test. As the number of random crossovers increases, the potential for damage at sidewall bearing points increases rapidly. It is one of the many reasons for conservatism in industry-recommended practices relating to the limits for SWBP but was absent in the tests.

10. The steel conduits used in the tests develop low coefficients of friction with slight lubrication and are not damaged by cable or fiber pulling lines, whereas ducts of other materials (plastic, transite, fiber) are more readily damaged and, in turn, affect the friction and damage potential to cable. Duct materials other than steel were used in certain portions of the Watts Bar plant, but not evaluated in the test.

Several major technical issues also bring into question the applicability of the test results:

1. The tension necessary to move the cable loop through the test rig was not measured so there is no means of determining or investigating the actual coefficients of friction. (The tension in the cable loop was monitored.)

2. There was no program to investigate the conditions necessary to damage cable, or what the mode of or symptoms of damage might be for the several cable constructions tested. Had such "fragility" tests been made, then it is likely that a reasonable engineering assessment could be made as to what actual cable pulling conditions and cable constructions represented the most limiting case that would be expected to lead to cable damage. As it is, it seems unfounded and illogical to assume that the test conditions represent the most adverse conditions in the plant.

3. The quick-rise ac breakdown tests used by TVA to evaluate possible damage during the SWBP program consisted of a rapid continuous rise in test voltage until breakdown occurred. However, ac stepped voltage tests having a 5- to 30-minute dwell time at successively higher steps in voltage until breakdown occurs are recognized in insulation science as well as cable engineering practice as much more effective in searching for either manfacturing defects or installation and service-incurred damage. That is why, for instance, such tests are used in AEIC cable qualification tests (not nuclear qualification tests) as cited in their CS5- and CS6-1982 specifications. The distortion or partial disruption of insulation or shield systems due to excessive SWBP would be best detected by extending the time of standard industry ac step tests. Using a quick-rise test will tend to miss evidence of damage observable by longer term ac overvoltage testing.

The great majority of cable installation pulling damage seen by and reported to the FRC team members over the years has resulted from cable jamming, combined SWBP and drag around bends due to inadequate lubrication, scuffing and cutting of cable by the conduit after the pull line had grooved the inside of conduit bends, saw-through of cable jackets and insulation during pullbys, and pulling cables over sharp or rough edges at the end of a conduit. Direct SWBP damage to cables in well lubricated duct bends or over large sheaves has not been a source of problems in the FRC team's experience. However, direct SWBP damage has been experienced where several small rollers were used in place of a large sheave. Therefore, the TVA tests for damage to well lubricated cables passing straight over smooth conduit bends represent a search for a damage threshold seldom experienced in practice and that is not representative of the Watts Bar conditions that would likely have inflicted damage on cables being installed there.

While the test has yielded interesting information on the tolerance of cables to direct radial SWBP, the results are probably quite the same as would be found by running cables over sheaves of similar geometry to that of the conduit bends. However, shear forces parallel to the direction of travel in the jacket and insulating material induced by high SWBP coupled with significant friction coefficients (less than ideal lubrications as probably occurred under the conditions at the Watts Bar plant) can be expected to induce more and different damage effects than radial forces (SWBP) alone. These shear forces were not evaluated during the TVA test program.

9. BEND RADIUS CONCERNS

The recent industry research and development work in connection with cable installation has focused on sidewall bearing pressure and pulling tension. No definitive work has been done regarding bending radius because it was assumed that the limitations of sidewall bearing pressure dictated generous curves around bends during installation. Manufacturers' literature provides the minimum values for the radii to which insulated cables may be bent for permanent training during installation. However, these limits do not necessarily apply to the radii for conduit bends, sheaves, or other curved surfaces around which the cable may be pulled under tension while being installed. During pulling, larger radii may be required to limit sidewall bearing pressure.

Published documentation for smaller allowable radii than the generally accepted values, which have been in use for years, is not available. It is known that tighter bends than those recommended by manufacturers have sometimes occurred in actual practice. The problem is to quantify the minimum allowable radius for specific types of cable and applications.

9.1 MINIMUM PERMANENT BEND RADIUS FOR 8-kV SHIELDED CABLES

TVA uses 8-kV rated cables in its 6.9-kV electrical system. These cables have either crosslinked polyethylene (XPLE) or ethylene propylene rubber insulation over the conductor. The insulation is covered by an extruded semiconducting layer, which, in turn, is covered by a spiral-wound, copper-tape shield or a set of spiral copper wires used as a shield. The shield is covered by the cable jacket. The purpose of the semiconducting layer is to provide a means for draining charges from the insulation surface to the shield such that corona discharge does not occur. Corona discharge can cause insulation damage and eventual electrical failure. Overbending of a shielded, 8-kV cable can cause damage to the interfaces between the shield and the semiconducting layer, the semiconducting layer and the insulation, and the insulation and the conductor. Gaps between the shield and the semiconducting layer should not cause any immediate problem since the semiconducting layer will allow charges to drain to the shield material surrounding the gap. Long-term deterioration could occur if the conductivity of the semiconducting layer changes and it can no longer drain the charges; corona discharges can damage the insulation. Deterioration of the semiconducting layer depends on the conservatism of the cable design and the environment of the cable. Oil-laden environments will tend to cause deterioration of the semiconducting layer. It should be noted that Yellow-77, which was used in pulling many cables at the Watts Bar plant, contains oil.

Disruptions of the interface between the insulation and the semiconducting layer and between the insulation and the conductor would have a more immediate effect since corona discharge would occur immediately. These disruptions could occur from severe bending abuse or from more moderate abuse if the cable were not tightly made (e.g., the semiconducting layer was not tightly adhered to the insulation).

With regard to testing of cable samples to assess the effects of cable bending abuse, corona discharge testing should detect the gross effects of dislodging the semiconducting layer from the insulation, and the insulation from the conductor. However, it will not detect the more subtle interruptions between the semiconducting layer and the shield. Therefore, corona discharge testing could be used to detect gross damage, but would not provide assurance that no age-related deterioration will occur. Corona discharge testing equipment is not suitable for in-situ use.

The cables with the highest probability for gross abuse are those Okonite cables that may have been bent to a radius 4.4 times the outside diameter of the cable. Okonite requests that these bends be remade to radii that are 8 times the cable diameter. Corona testing of a new Okonite specimen in a laboratory could be performed to determine the initial level of corona discharge and the inception and extinction voltages when the cable was unbent, these parameters at a radius smaller than 4.4 times the cable diameter, and the parameters at a reformed radius of 8 times that cable diameter. If significant changes in corona discharge levels or inception and extinction voltages occur when the cable is overbent or when it is returned to a larger radius, it is indicative of a significant level of damage and corrective action should be taken (i.e., replace the cable).

If a significant change in corona does not occur when the cable is overbent or returned to a larger radius, it indicates that gross damage did not occur immediately. However, age-related deterioration associated with gaps between the shield and the semiconducting layer cannot be ruled out. Therefore, TVA should develop a program to evaluate all failures of 8-kV cable when they occur to determine if the failure was associated with overbending and to determine if further corrective action is needed for like cables (i.e., determine the need for replacement of all similarly installed cables of the same manufacturer).

9.2 MINIMUM BEND RADIUS FOR LOW VOLTAGE CABLES

Low voltage cables are most affected by failure mechanisms associated with mechanical forces when subject to tight bends rather than by the corona discharge phenomenon that affects medium voltage cables. A sharp bend in low voltage cable puts a high compressive stress on the inside of the cable and tensile stress on the outside. In large cables, considerable force is required to sustain these bend stresses. When the forces are exerted on the cable by sharp corners of surrounding components, there is a risk of failure through indentation and rupture of the insulation, especially under high temperature conditions. For cables subject to accident environments, the stresses associated with tight bends will increase the probability of failure even when the cable is not restrained by sharp corners. The added mechanical stresses in the cable insulation from severe bends coupled with the harsh temperature and steam environments will tend to cause insulation failures as has been observed by FRC team members who have performed qualification tests.

9.3 TEMPORARY BENDS

The discussions for permanent bends are generally applicable to temporary bends except that the mechanical stresses are relieved. For shielded cables, 6.9-kV and higher, structural damage incurred by temporary sharp bends can lead to long-term electrical degradation and random failures. For low voltage cables with shields, the largest concern is the possible disruption of the shielding system, causing a loss of its effectiveness in controlling electrical noise in the associated circuit.

While manufacturers are reluctant to give general relief for minimum bend radii for medium voltage cable, there is one obvious guideline for temporary bending which many manufacturers have agreed to and use continually. It is the ICEA Publication A9-428, NEMA WC6-1975 (R1980), "Drum Diameters of Reels for Wires and Cables." The H-2 tables of the current ICEA Specifications S-68-516 Dec. 1984 (for EPR) and S-66-524 Dec. 1984 (for XLPE) use the same exerpted information from A9-428. These guidelines for minimum drum diameters of various cables imply cable bending radii of five times the cable outer diameter for 0 to 2000 V, non-shielded cables, either single or multiconductor, and seven times cable outer diameter for tape-shielded cables over 2000 V. A footnote allows the outer diameter to be considered that of the shielding tape when it is covered with a rubber or plastic jacket. These same standards do impose permanently installed bending radii as currently used by TVA in G-38, R8 for cable training radii except that there is no provision in any ICEA standard for using the diameter of the insulation of the largest single conductor of a multiconductor cable as a multiplier.

There are two broad classes of insulation used in these cables: crystalline and amorphous. Polyethylenes are examples of the tougher, crystalline type at normal temperatures, whereas the rubber-like ethylene propylene rubbers are amorphous and more compliant. Unfortunately, many blends of materials fall in between. Cable manufacturers that have suggested relief for temporary TVA bends are those that supply the amorphous material only. The amorphous materials are more forgiving of bending stresses.

Temporary bending radii that are less than the published industry practice for permanent bends should be limited to those given by a specific manufacturer unless additional data can substantiate a lesser value.

9.4 COMMENTS ON PROPOSED RESOLUTION METHOD FOR LOW VOLTAGE CABLE BEND RADIUS VIOLATIONS FOR HARSH ENVIRONMENT CABLE

The primary concern for low voltage cables that are bent to less than the minimum allowable bend radii of four times the cable diameter is failure under accident environment conditions.

During the meeting with TVA in Knoxville, TN, on July 17, 1986 and again during the meeting of September 23, 1986 at the Sequoyah plant, TVA's consultant, K. Petty, of Stone & Webster Engineering Corporation, described the proposed method of resolution for bend radius violations for low voltage cable. This method assumes that the minimum bend radius that actually occurred in the Watts Bar plant is equivalent to one cable diameter as opposed to the required radius of four times the cable diameter. TVA has obtained cable specimens that were subjected to a research qualification program. Elongation-at-break data were available for the insulation of the cable following pre-conditioning prior to accident condition exposure. TVA had elongation-at-break tests performed on the samples that had completed the program. TVA proposes to use the elongation-at-break data to evaluate the capability of insulation on a cable bent to a radius of one diameter to withstand an accident environment. The assumption made is that if the insulation is capable, after exposure to an accident condition, of elongation without break to an extent greater than the elongation of the outer surface of the insulation when the cable is bent to a radius one times its diameter, then it could have withstood the accident environment while bent to a radius of one diameter. However, the elongation-at-break tests from before and after the accident exposure were performed at room temperature and not at accident simulation environment temperatures. At present, there are no known models for extrapolating the capability of cable insulation to withstand elongation stresses from room temperature conditions to an accident temperature condition while subjected to steam, pressure, and spray. The modes of cable failure during LOCA-type tests that have been observed by members of FRC's team suggest that the added mechanical stresses from severe bends could substantially contribute to the promotion of failures even though the cable materials were found to be flexible after the test was completed. Therefore, for harsh environments, prudent practice should assure that Class 1E low voltage cables are not bent beyond the radius recommended by the manufacturer.

10. SUPPORT OF VERTICAL RUNS

Support of cable in vertical conduit runs is not well treated in TVA procedures. No guidance or concern was evident in 1979 G-38 specification, and current TVA standards lack recognition of the extreme duress to cable under tension passing through 90° condulets that are located at or near the top of a vertical run. During the second site visit, a 90° condulet within containment was observed at the top of a vertical run with high tension in the small cables. A 90° condulet was also observed in a horizontal run with high cable tension. Because the inside corners of standard condulets commonly have radii of 1/16 to 1/8 inch, tension in cables passing through the condulets causes potential for severe damage from indentation and cutting of the jacket and insulation. The overall bending radius of the cable in the condulet may appear quite reasonable due to the intrinsic stiffness of the cable, but compound flow and cut-through of the insulating material can result at normal ambients. The effect of a sudden harsh, high temperature environment may be to cause multiple common mode failures if many cables are in tension where they pass through 90° condulets.

The vertical support limits of NEC Article 300-19 used by TVA in G-38 R8 Section 3.2.1.9 assume adequate support devices have been used on conduit bends at the top of the run. However, 90° condulets some distance from the top of a vertical run may still cause damage to a cable. The issue of horizontal conduit runs' ability to restrain movement and tensions from vertical runs is complex and debated in the industry. Field reports of damage related to vertical runs have dealt primarily with large cables for several reasons, but the engineering principles are known and appear to be applicable to small cables that are subjected to either thermal cycling or mechanical vibration. Cables creep with an effective coefficient of friction near zero when they are subjected to these cyclic stresses. Vertical cable runs try to creep downward and pull on the upper horizontal cable section and push on the lower horizontal cable segment. Small cables snake in the lower horizontal run and pass the vertical tension through the upper horizontal run for distances beyond those that normal static or moving friction forces would be expected to permit. Therefore, tension in and forces acting on the cable at long distances from the top of vertical runs may be close to (and, in some cases, higher due to thermal cycling) the tension at the top of the vertical run. At present, there is a lack of agreement in the industry concerning the horizontal length of the cable that vertical runs influence. However, conservative engineering would certainly dictate that no 90° condulets with sharp inside corners be installed near the top of vertical runs within horizontal distances from the top of a vertical that are as long as the length of the vertical run itself. A 90° condulet may be allowed closer to the top of a vertical run only if the vertical run is properly supported.

The 90° condulets carrying cables under tension represent a major potential for damage to cable in the Watts Bar plant, especially in harsh thermal and wet environments. Fortunately, the risk can be reduced through inspections to determine if tension exists in cables at the point of contact with the 90° condulet corner. Corrective measures, when necessary, are often practical and effective. Unfortunately, the creeping progression of tension in the vicinity of vertical runs occurs over years of operation so that the potential for, as well as immediate evidence of, tension should be assessed for installations that are a few years old as well as for new installations.

11. OBSERVATIONS OF CABLE INSTALLATION DURING SITE VISIT

During the visits to the Watts Bar plant on July 18, 1986 and September 9 and 10, 1986, the FRC team members inspected terminations, pull boxes, and condulets to observe the condition of cables at various points along the conduit runs. During the July 18, 1986 visit, the FRC team concentrated on 12 conduit runs that TVA determined to be the worst case with respect to sidewall bearing pressure violations. In addition, manhole No. 22 was inspected because it was specifically addressed in one of the employee concerns as being "interesting." Prior to the September 9 and 10, 1986 plant visit, FRC reviewed 82 isometric drawings that TVA had used to determine the 12 worst-case conduits. From the 82 isometric drawings, FRC determined other conduits that merited inspections because of configuration, cable types, and seeming difficulty of the pulls. The team also inspected the second section of manhole 22 and the switchgear terminations of 480-V and 6.9-kV cables.

Most of the cable in the conduits cannot be inspected. However, by inspecting both terminations of the cable and any pull points, it might be possible to observe gross damage to the cable from pulling. If permanent bend radius violation existed, some of these might be also be observed. The purpose of the inspections was to get an overall feeling of the quality of the installation and to determine if gross damage had occurred on a consistent basis. Power (480-V and 6.9-kV), control, and instrument cables were included in the sample.

The inspections yielded no significant indications of cable abuse from pulling at the terminations or mid-conduit run pull points that could be inspected. Some pull boxes, such as those for conduit No. 2PLC2763A, were located in awkward, congested areas where covers could not be removed for inspection. In the case of one conduit (No. 1PP2188A) containing shielded, 6.9-kV cables, a straight condulet was opened for inspection. If the conduit was used as a pull point, overbending of the cables would have occurred. If it had not been a pull point, the overall cable pull would have included 778° of bends in 60 ft, causing a high potential for damage to the cable. Unfortunately, the condulet was filled with fire stop foam. However, the condulet was also half way filled with water, indicating that condensation could occur in the Watts Bar conduits. The termination of the cable associated with this condulet showed no signs of distress to the cable insulation.

Inspection of the termination of the 480-V power cable from conduit 1PLC-2940A at Cabinet No. 1-BD-212-A1-A revealed a concern not relating to cable pulling or bend radius. The cable from one phase was firmly against a different phase of the bare bus. A potential for an eventual phase-to-phase fault exists. Figure 1 is a picture of this configuration.

The site inspections heightened the concern relating to the number of 90° condulets used in the conduit system, especially those used at or near the tops of vertical runs. Figures 2 and 3 show conditions typical of the concern. Although the radii of the bends of the cables do not exceed the limit for cable bends, the entire weight of the vertical portion of the cable is supported by the inside corner of the 90° condulet, causing a marked indentation. Under harsh temperature conditions, failure of the cable insulation is possible.

The 6.9-kV cable terminations that were inspected did not show any signs of abuse from pulling or bending. However, at the switchgear end of the cables, where the cables entered the tray system, it was noted that the permanent bend radius for a number of cables appeared to be less than the minimum allowed under the TVA specifications. The bends appear to have radii on the order of six times the cable diameter. One such bend is shown in Figure 4.

The inspection of manhole 22 identified a number of concerns about the use of good installation practices. Many of the conduits entering the manhole had sharp rough edges. No bells had been installed to support the cable at these edges. The cables also ran across the edges of the trays with no support or padding. Many of the conduits had pull ropes in them for future use. While it was stated that these pull ropes had been abandoned, their existence indicated that a large number of pullbys were expected and had occurred. Various views of the conduits and trays in manhole 22 are shown in Figures 5, 6, and 7. During the July 18 visit, a large figure eight loop of control cable was found hanging over the ladder for the manhole. The full weight of the cable was supported by the two sharp edges of the ladder support. The cable had been pulled into one side of the manhole and it is assumed that the loop of cable would be pulled out of the other side of the manhole. The cable could have been carefully laid on top of one of the cable trays rather than looped on the ladder. On the ladder, it was being abused by the support points and anyone climbing on the ladder.

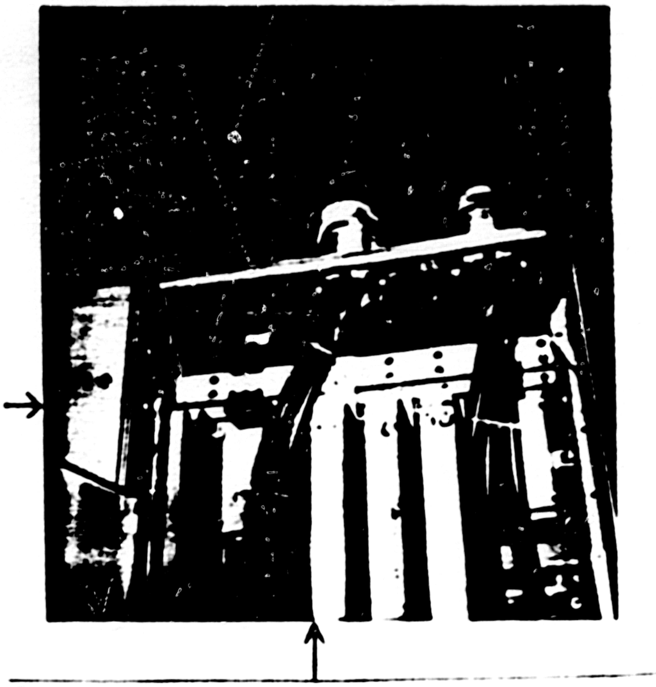

Figure 1. One Phase of a 480-V Cable Indented by the Bus of a Different Phase in Cabinet 1-BD-212-A1-A (at (at intersection of arrows)

Figure 2. T Condulet with Cables Entering a Vertical Section of Conduit

Figure 3. 90° Condulet at the Top of a Vertical Run Showing the Corner Supporting the Cable

Figure 4. Medium Voltage Cable Bend Radius of Approximately 6 Times the Cable Diameter

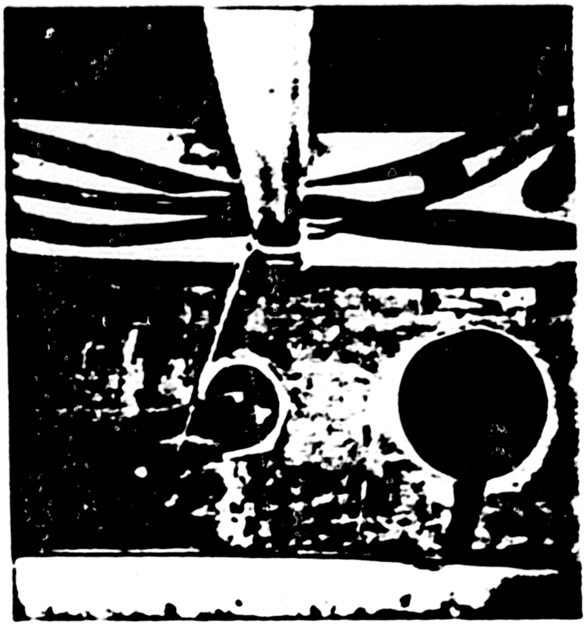

Figure 5. View of Manhole 22 Showing Pull Ropes (Originally Installed for Future Use) Wrapped Around a Cable and Unsupported Cable Resting on a Sharp Conduit Edge

Figure 6. View of Manhole 22 Showing Mixes of Cable Constructions Pulled in the Same Conduits

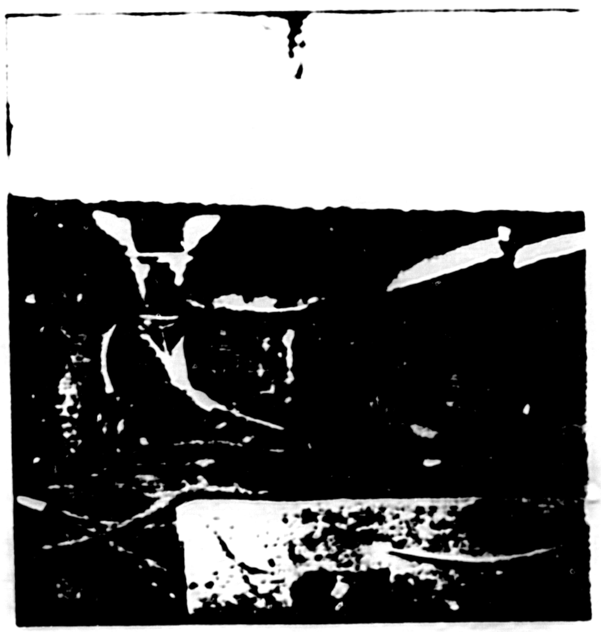

Figure 7. View of Manhole 22 Showing Mixes of Cable Constructions in the Same Conduits and Additional Pull Ropes

12. EFFECTS OF CABLE INSTALLATION DAMAGE AND EXCESSIVE BENDS ON FUNCTIONAL CAPABILITY

12.1 JACKET AND INSULATION MATERIAL CUTTING, TEARING, AND SAWING DURING INSTALLATION

As described in previous sections, numerous conditions during installation can lead to cutting, tearing, and sawing damage of cable jacket and insulation materials. During pullbys, the moving cable and pull rope will tend to saw through the stationary cables if the moving cable crosses the stationary cable at a bend. When mixes of types and sizes of cables are pulled, smaller, softer cables may cross under the bulk of the cables and be crushed and torn as they pass around bends. When three or four cables are pulled into conduits where jamming is possible (see Section 7), a full jam will break the pull rope or the cable, and the cable will be removed and the conduit will be reworked. However, the higher concern is when cables just begin to jam, and the insulation and jacket are subjected to shear stresses that can tear them. For most cases, damage from sidewall bearing pressure by itself is not of high probability. The EPRI EL-3333 study [11] and the TVA study [1]* indicate that the cables can withstand much higher sidewall bearing pressures than originally specified by manufacturers. However, sidewall bearing pressure would be of high concern if cables were pulled over the sharp inside corners of 90° condulets. While it is hoped that such a condition did not occur, the large number of 90° condulets used and the method of helping a cable along (see Section 4.3) through condulets indicates that some cables could have been pulled under high tension around the sharp corners of 90° condulets.

Of the pulling conditions that may lead to immediate insulation damage, jamming of the cables is of highest concern for medium voltage (6.9-kV) cables at the Watts Bar plant. Medium voltage cables are comprised of three single-conductor cables at the Watts Bar plant. One three-phase circuit is allowed in a duct. This limitation eliminates the concern for pullbys and for mixed

*Although this Technical Evaluation Report finds problems with the applicability of the TVA study to plant conditions, it does not disagree with the basic results.

cable pulls. Since very few 90° condulets were installed in medium voltage cable conduits, the concern for pulling the cable through such condulets is greatly reduced.

The damage to medium voltage cable from partial jamming will most probably cause disruptions between the shield and the insulation and between the conductor and the insulation. Such disruptions will cause voids or discontinuities in potential gradients, leading to corona discharges that could cause failure of the insulation. The condition would lead to significant degradation only in cables that are energized most of the time and would result in random failures rather than common mode failures. Such failures would tend to reduce the overall reliability of the electrical system.

Pullbys and mixed pulls would not be of concern for low voltage power cable of sizes greater than 8 AWG, which were also routed in individual conduits in groups of three single conductors. The effects of partial jamming and pulling cable around condulet corners would be the same as those for low voltage control and instrumentation cable noted below.

For low voltage control and instrumentation cables (up to 480 V), all of the conditions leading to cutting, tearing, and sawing apply. At low voltage levels, nearly or completely penetrated jackets and insulations could exist in dry conduits without electrical failure under normal plant conditions. Dry air is a good insulator and pierced insulation may not be distinguishable from perfect insulation under most available electrical tests for unshielded cables.

The key concerns relating to cutting, tearing, and sawing of low voltage power, instrumentation, and control cable are accident environments and moisture. Moisture accumulation can occur due to condensation under normal power plant conditions. One duct was found to be wet during the second site visit. With cuts or tears in the insulation, water would provide an electrical path between the conductors or between a conductor and the steel conduit. Under normal conditions, such failures would tend to be random rather than common mode since many conduits would not become moist at the same time. However, under accident temperature and steam conditions, electrical failures associated with previously undetected cuts and tears of insulation would represent a common mode failure mechanism and could affect the operation of a significant amount of equipment.

12.2 EXCESSIVE BENDING OF CABLE

12.2.1 Medium Voltage Cable Bending

Excessive bending of medium voltage cable can also disrupt the continuity of the interfaces between the shield and the insulation and between the insulation and the conductors. The disruption can lead to corona discharge and possible long-term failure. Such failures are of a higher probability in cables with crosslinked polyethylene insulation since the insulation is more susceptible to corona attack than is ethylene propylene rubber. TVA has a number of different types of medium voltage crosslinked polyethylene cable in use at the Watts Bar plant. With regard to temporary bending of the cable, some relief may be assumed based upon allowable reel drum size contained in ICEA Standards S-68-516 and S-66-524 that allow a reel drum radius of seven times the cable shield diameter. However, case-by-case relief from standard permanent bend limits must come from the manufacturer of the cable.

12.2.2 Low Voltage Cable Bending

The primary concern for low voltage cable bent to a very tight radius (i.e., a radius of one diameter versus the recommended minimum of four times the diameter) is failure under harsh temperature and steam environments. Under normal plant environments, sharp bends in the cable should not cause sufficient tensile or compressive stress to cause mechanical failure of the cable coverings. However, under accident conditions, the behavior of the cable when bent to a radius of one to four diameters is not known. Mechanical failure of the jacket and insulation followed by electrical failure may occur.

12.3 SUPPORT OF CABLES UNDER TENSION BY SMALL SURFACE AREAS

The inside corners of 90° condulets provide a very small supporting surface to cables that pass over them. If the cable is under tension, the corner will tend to indent and cut the insulation and the conductors of some cable will tend to creep through the insulation. The tension in the cable may result from the weight of long vertical runs of cable if the 90° condulet is located at or near the top of the run or it may result from residual pulling tension in constrained cables. NUREG/CR-4548 [12] provides some insight for ethylene propylene cables with Hypalon jackets under such conditions and indicates that creep-through of the conductor would not be expected for a period of 5 years. Rigorous extrapolation beyond 5 years cannot be made. However, for accident conditions, creep-through or mechanical cracking followed by electrical shorting could be expected. The report recommends that cables be provided with large radius supports or stress relief. The report provides no information for other cable constructions. Published information indicates that crosslinked polyethylene and plastic insulations and jackets are more susceptible to mechanical deformation when subjected to temperatures greater than 100°C. The deformation properties of silicone rubber tend to be less dependent upon temperature, but depending on the specific compound used may be much more prone to creep than are ethylene propylene rubber insulations. Therefore, crosslinked polyethylene, plastic, and silicone rubber insulated and jacketed cables subject to high temperature accident conditions should not be subjected to high mechanical stresses such as those resulting from cable tension at the corners of 90° condulets.

13. TVA MONITORING PROGRAMS FOR INSTALLED CABLES

In Reference 2, TVA listed two types of planned monitoring of the installed cables at the Watts Bar plant. Periodic electrical testing will be performed on the cables of medium voltage motors and low voltage motors of 100 hp and greater. The type of testing is not described. The testing is TVA's standard practice and has not been initiated because of cable installation concerns. Although a good practice, electrical testing will probably not detect the types of damage or deterioration modes expected. Furthermore, no testing of low power, low voltage circuits is planned.

The second type of monitoring is a trend analysis program to track, consolidate, and categorize conditions adverse to quality. Such monitoring will be implemented at the Watts Bar plant by November 1986. The trend analysis program will be used to identify trends associated with cabling at any TVA nuclear plant. The details of the types of parameters to be monitored by the program and the types of trends to be analyzed were not provided by TVA.

14. CONCLUSIONS

Evaluation of the cable pulling and bending practices at the Watts Bar plant reduced the concern for some types of potential problems and heightened the concern for others. The following summarizes the conclusions relating to each significant concern.

1. Standards and Procedures

   Revision 2 of G-38, the controlling standard during the bulk of the cable pulling, did not reflect the state of knowledge in the industry at that time. Support of cables in vertical runs, control of pullbys, and prevention of jamming are not covered. Tension control limits for sidewall bearing pressure are not labeled as such and are described as alternate limits rather than limits that must be met simultaneously with the limit for cable stretching.

   Revision 8 of G-38, the present version, rectifies many of the omissions from Revision 2, but may be confusing to the intended users since it contains a mix of practical statements and theory. While pullbys are addressed, the requirements for their control are very weak. Support of cable in vertical runs when 90° condulets are used near but not at the top of the run is not addressed nor is control of jamming of cables during pulling.

2. Pulling Practices

   The procedures and controls in place during most of the conduit construction and cable pulling placed the bulk of the responsibility for the details on the electricians performing the work. The electricians and their foreman chose the routing, locations of pull points, and the types of pull points to be used. The cable installations were not engineered. Tension and sidewall bearing pressure calculations were not required at the time of the bulk of the cable pulling.

3. Calculation of Sidewall Bearing Pressure

   The calculations performed in 1985 to determine the worst-case conduit runs did not take into account the type of lubricant used from 1978 to 1982, nor did they account for the lack of independence between pull segments as described by the electricians on September 9, 1986. If the electricians "helped" the cable along at pull points rather than pulling the cable out of and then back into a pull point, the tensions between segments are not independent. Therefore, the calculations are not fully representative of the actual conditions. For such back calculations where there are many unknowns regarding lubrication methods, a coefficient of friction of 0.6 to 0.7 is suggested. For pullbys, an even higher coefficient, such as 1.0, should be used.

4. Sidewall Bearing Pressure Damage

Based on the results of the TVA SWBP tests and those documented in EPRI EL-3333, SWBP damage is not considered to have been a significant concern except for the cases where cable was pulled around the corner of 90° condulets or through flexible conduits having tight bends. The number of 90° condulets and the described method of helping cables through pull points causes a concern to remain that some cables were pulled through 90° condulets and may have been damaged.

5. Pullby Damage

Pullbys did not occur on medium voltage and large-conductor, low-voltage power cable. However, a large number of pullbys did occur on control and instrumentation cable runs. There is a great concern that the moving pull rope and cable could have sawed through insulation of the stationary cables, causing the potential for circuit failure during conditions where the conduit is wet or exposed to high temperatures. Normal condensation in the conduits is expected to cause random failures. An accident condition could produce multiple common mode failures.

6. Jamming Damage

TVA's procedures contain no limits relating to prevention of jamming damage. While full jamming would break the pull rope or the cable being pulled, the higher concern is for cable that partially jams and pulls free. Tearing of the insulation and disruption of the interface between the shield and conductor interfaces with the insulation are of concern. The cables that are of highest concern are power cables that are pulled in groups of three and are prone to jamming.

7. Permanent Bending Damage and Stresses

For medium voltage cable, TVA is verifying the permanent bend radius of the cables and, where violations exist, restoring the cable to an appropriate radius.

For low voltage cable, TVA is attempting to show that the accident withstand capability of a cable will not be affected by bending it to a radius of one times its diameter. As described in Section 9.4 of this report, there is no available extrapolation technique for concluding that the cable's capability after an accident simulation can be used to show the cable's ability to withstand stress under the accident environment.

8. Support of Cables Under Tension in 90° Condulets

Cables in 90° condulets at or near the top of vertical runs may be supported by the sharp corner of the condulet. Random failures due to cutting of the insulation and conductor creep may occur during normal service, and multiple failures can be expected in accident conditions.

Overall Conclusion

In general, the evaluation of the Watts Bar cable installations indicated that the system was installed in a less orderly fashion than would be expected for a nuclear power plant. Although no outright cable damage was found, the controls on the installation process were such that damage could have occurred from jamming, pullbys, severe bending, and tension through 90° condulets. Long-term random and accident-related common mode failures are possible for these types of damage. Further testing and evaluation of a sample of cables in conduits where pullbys occurred, and where jamming may have occurred, is necessary to assure that significant damage has not occurred. If the evaluation of the cables indicates that damage was significant, replacement of cables installed under similar conditions will be necessary.

15. RECOMMENDATIONS

These recommendations are based on the conclusions contained in Section 14. The purpose of the recommendations is twofold. For those types of damage that are observable through testing and inspection, the purpose is to gain further assurance that installation abuse did not lead to significant amounts of damage. For those types of damage that are more subtle and could lead to age-related failures, the purpose is to prevent multiple failures by evaluating each individual failure to determine the cause and taking corrective action for all cables that are similar and have been similarly installed. The following recommendations are made to assure adequate reliability of the cable system.

1. Monitoring of Cable Failures

A prime recommendation resulting from the evaluation is that each cable failure that occurs at the Watts Bar plant in or near a conduit bend or sharp cable bend should be evaluated to determine the cause of the failure. If the failure is the result of cable pulling damage, the cables of the same type that were installed under similar conditions should be evaluated for replacement.

With regard to implementation of a cable deterioration trend analysis system at the Watts Bar plant, it is recommended that TVA treat each cable failure as being highly important until it can be proven that the failure is not related to cable pulling or bending and does not indicate that the other cables in the plant are prone to the same mode of failure. The program should include a commitment to prompt corrective action for similar cable installations if the cause of failure is found to be related to installation abuse.

2. 90° Condulets and Vertical Runs

With regard to 90° condulets at or near the top of vertical conduits, installation of appropriate cable supports is necessary. The techniques described in Section 3.2.1.9 of G-38 R8 are appropriate. For silicon rubber insulated cables, the worst-case conduit with a vertical cable run supported by a 90° corner of a condulet should be electrically tested via a dc high potential test to determine if insulation failure due to installation damage or conductor creep is a significant concern. If no electrical failure occurs, the cable should be resupported. If electrical failure does occur, the cable should be replaced and a further sample of worst-case should be tested to determine the scope of the problem.

3. Pullbys

To evaluate the degree of damage that occurred from pullbys, TVA should analyze the known pullbys to identify the conduit having the highest susceptibility to cable sawing damage during the pullby, and remove the cable from that conduit for inspection and testing to reveal any presently hidden damage. If significant damage is found in this cable, a commitment to appropriate remedial actions for cables in other conduits with pullbys is necessary.

4. Small Bend Radii for Low Voltage Cable

TVA must take appropriate action, such as testing, to assure that low voltage power, control, and instrument cables that are bent to radii smaller than four times the cable diameter will not be subject to common mode failures when subjected to accident and post-accident environments.

5. Small Bend Radii for Medium Voltage Cable

TVA must determine those 8-kV shielded power cables that are bent to radii smaller than those presently recommended by the manufacturers of the cables and take action to assure that the cables will not be subject to long-term degradation that could interfere with the reliability of the cables. A possible means for detecting long-term degradation is periodic dc high potential testing of a sample of cables that had the worst-case bends.

6. Jamming

TVA must evaluate conduits containing three or four cables whose diameters when compared to those of the conduits could lead to jamming. For those conduits where jamming and partial jamming could have occurred, TVA must take further action to assure that significant damage has not occurred to the cable such that the cable's reliability is reduced or common mode failures could occur when the cables are subject to harsh (wet) environments. One possible means of providing such assurance is to remove cable from a conduit where a high probability for jamming would have been expected and to perform detailed electrical testing and physical evaluation.

7. Pulling Through 90° Condulets and Flexible Conduit

TVA must make a survey and assessment of flexible conduits with a significant offset or angle of bend and of 90° condulets to determine those that were likely to have had cables pulled through them under mechanical assistance (e.g., capstans, come-alongs). If such conditions are found, a diagnostic and remedial program must be performed to determine the extent of the damage and to remove cables with significant levels of damage from service.

8. Revision of General Construction Specifications

TVA should revise General Construction Specifications G-38 and G-40 to eliminate omissions and to remove unnecessary complexities and nonconservative elements. The revision should include discussions of jamming and of limiting tension with respect to SWBP. Limitations should be placed on use of 90° condulets at or near the top of vertical conduit runs. Clear guidance on limiting pullbys and providing tighter control of pulls when pullbys must be performed should also be included. Controls on the use of all types of condulets in conduits should also be added for medium voltage cable and, to the extent necessary, for large low voltage cables to prevent abuse from bending during pulling.

16. REFERENCES

1. Letter from W. S. Raughley (TVA) to G. Toman (FRC) dated July 10, 1986 forwarding an advance copy of the TVA report, "Cable Sidewall Bearing Pressure Tests," dated May 30, 1986

2. Letter from R. L. Gridley (TVA) to Mr. B. J. Youngblood (NRC) dated October 7, 1986, which responded to 16 NRC questions relating to cable pulling issues

3. TVA Division of Engineering Design, General Construction Specification No. G-38, "Installing Insulated Cables Rated Up to 15000 Volts Inclusive," Revision 2, August 3, 1978

4. TVA Office of Engineering General Construction Specification No. G-38, "Installing Cables Rated Up to 15000 Volts," Revision 8, March 17, 1986

5. Watts Bar Nuclear Plant, Modifications and Additions Instruction, MAI-3, "Installation and Inspection of Insulated Control, Signal, and Power Cables Units 1 and 2," Revision 6, January 15, 1986

6. Watts Bar Nuclear Plant, Modifications and Additions Instruction, MAI-3, "Installation and Inspection of Cable Terminations," Revision 4, June 27, 1986

7. Watts Bar Nuclear Plant, Modifications and Additions Instruction, MAI-13, "Installation of Conduit and Junction Boxes, Revision 3, September 5, 1986

8. Internal TVA Memorandum from W. S. Raughley dated September 2, 1986, Subject: "All Nuclear Plants - Electrical Issues - Class 1E Cable Bend Radii." (Forwarded as an Enclosure to Reference 2 above)

9. Internal TVA Memorandum from W. S. Raughley dated July 16, 1986 Subject: All Nuclear Plants - Electrical Issues - Support of Cables in Vertical Conduits." (Forwarded as an enclosure to Reference 2 above).

10. G. C. Weitz, "Coefficient of Friction Measurement Between Cable and Conduit Surfaces Under Varing Normal Loads," IEEE 84 T&D 375-2, Institute of Electrical and Electronic Engineers, New York, 1984

11. D. A. Silver, G. W. Semon, L. R. Bush, "Maximum Safe Pulling Lengths for Solid Dielectric Insulated Cables," EPRI EL-3333, Electric Power Research Institute, Palo Alto, CA, February 1984

12. M. Steutzer, "Correlation of Electrical Reactor Cable Failures with Material Degradation," NUREG/CR-4548, U.S. Nuclear Regulatory Commission, Washington, DC, March 1986

APPENDIX A

SUMMARIES OF TVA EMPLOYEE CONCERNS RELATING TO CABLE PULLING AND BEND RADII

FRANKLIN RESEARCH CENTER
DIVISION OF ARVIN/CALSPAN
20th & RACE STREETS, PHILADELPHIA, PA 19103

SUMMARY OF EMPLOYEE CONCERNS
PULLING PROCEDURES

EC #	SUMMARY
IN-85-018-004	SUPERVISOR WOULD NOT FOLLOW CABLE PULLING PROCEDURES (WORKED WITHOUT PERMITS).
IN-85-213-001	CABLING PULLING PROCEDURES WERE CHANGED AROUND 1981. ITEMS SUCH AS PULL TENSION WERE MODIFIED.
IN-85-295-003	CABLE PULLS WERE PERFORMED IN A "RUSHED" MANNER. CABLES WHICH WERE PULLED UNDER THE OLD "UNCONTROLLED" PROCEDURES WERE POSSIBLY NOT RECHECKED.
IN-85-856-005	THE PRACTICE TO USING BREAK ROPES WHEN PULLING CABLES DID NOT BECOME EFFECTIVE UNTIL 1984. ALL THE "BIG" PULLS OCCURED 3+YEARS AGO WITHOUT BREAK ROPE.
IN-85-935-001	70% TO 75% OF THE INSTALLED CABLE IS BAD AND SHOULD BE REPLACED. CABLE WAS NOT PULLED IN ACCORDANCE WITH PROCEDURES; BEND RADIUS WAS VIOLATED AND CABLE WAS NOT PROTECTED.
IN-86-199-001	CABLES PULL ARE NOT ALWAYS PERFORMED TO THE REQUIREMENTS OF QCI. BREAK LINKS WERE NOT USED DURING CABLES PULLS.

SUMMARY OF EMPLOYEE CONCERNS
PULLING PROCEDURES

EC #	SUMMARY
IN-86-254-001	ELECTRICAL CABLES PULLED BY TRUCK OR OTHER MEANS NOT ALLOWED BY PROCEDURE.
IN-86-259-014	CABLE BROKE DUE TO IMPROPER PULLING METHODS. CABLE WAS THEN SPLICED AND PULLED INTO CONDUIT.
IN-86-314-001	COMMON PRACTICE TO UTILIZE IMPROPER CABLE PULLING TECHNIQUES (WINCHES AND HAND COME-ALONGS).

SUMMARY OF EMPLOYEE CONCERNS
OVERFILLED CONDUITS

EC #	SUMMARY
IN-85-255-001	CONDUITS ARE OVERFILLED AND CABLES MAY HAVE BEEN DAMAGED. MAXIMUM TENSION FOR PULLING CABLE WAS EXCEEDED.
IN-85-436-004	CONDUIT OVERFILLED. PULL TENSION WAS NOT MONITORED.

SUMMARY OF EMPLOYEE CONCERNS
90 CONDULETS

EC #	SUMMARY
EX-85-157-002	LL AND LR CONDOLETTE FITTINGS CAUSE TOO GREAT A BEND FOR THE CABLES.

SUMMARY OF EMPLOYEE CONCERNS
BEND RADII

EC #	SUMMARY
EX-85-073-001	CABLE BEND RADIUS MUST HAVE BEEN VIOLATED. IN CORE INSTRUMENT ROOM. CABLES WERE SPLICED THEN STUFFED INSIDE THE FITTING.
IN-85-719-002	ELECTRICAL CABLES EXIT CABLE TRAY OVER A SHARP EDGE INTO A PENETRATION. THESE CABLES MAY ALSO VIOLATE MINIMUM BEND REQUIREMENTS.
IN-85-935-001	70% TO 75% OF THE INSTALLED CABLE IS BAD AND SHOULD BE REPLACED. CABLE WAS NOT PULLED IN ACCORDANCE WITH PROCEDURES; BEND RADIUS WAS VIOLATED AND CABLE WAS NOT PROTECTED.
WI-85-100-013	CABLE BENDING RADII PROBLEMS.

SUMMARY OF EMPLOYEE CONCERNS
MISCELLANEOUS

EC #	SUMMARY
WI-85-100-020	EXTREMELY BAD CABLE PRACTICES. CABLING IS ROUTED OUTSIDE TRAYS, COILED ON TRAY SUPPORTS OR FLOORS, TIED ON SIDES OF TRAYS AND SUPPORTS, AND TIED ON THE BOTTOM OF TRAYS. WIRES BENT 90 DEGREES INTO CONDUIT. PLASTIC CONDUIT BRIDGES BETWEEN CABLE TRAYS.

SUMMARY OF EMPLOYEE CONCERNS
UN-"SWABBED" CONDUITS

EC #	SUMMARY
IN-85-425-004	CONDUITS NOT SWABBED PRIOR TO CABLE PULLING.
IN-85-581-001	LARGE QUNTITIES OF ORGANICS WATER, ROCK+GRAVEL IN CONDUITS. CONDUIT NOT SWABBED.

SUMMARY OF EMPLOYEE CONCERNS
PULL - BYS

EC #	SUMMARY
IN-85-314-001	CABLE IS PULLED ONE AT A TIME AND THEREFORE THE TENSION EXCEEDS THE MAXIMUM VALUE DUE TO TANGLING IN UNIT 2.

SUMMARY OF EMPLOYEE CONCERNS
UNCONTROLLED TENSION

EC #	SUMMARY
EX-85-086-001	A CABLE WAS PULLED USING A "COME ALONG"
IN-85-046-001	EXCESSIVE FORCE (COME-ALONG) WAS USED IN PULLING CABLES AND MAY HAVE RESULTED IN DAMAGE TO CABLES.
IN-85-318-001	EXCESSIVE FORCE WAS USED TO PULL CABLES.
IN-85-318-002	EXCESSIVE FORCE (TRUCK) WAS USED TO PULL CABLES. WHITE NYLON ROPE BROKE & WAS BLACK FROM RUBBING AGAINST CABLE.
IN-85-323-002	EXCESSIVE FORCE DUE TO OVERLOADED CONDUITS WAS USED TO PULL CABLES. CAUSED DAMAGE TO CABLES.
IN-85-325-005	NUMEROUS NON-SPECIFIC INSTANCES WERE RELATED REGARDING OVERSTRESS OF CABLE DURING PULLING OPERATIONS. SUFFICIENT SEVERITY TO CAUSE MULTIPLE INSTANCES OF 1 INCH MANILA BREAKING.

SUMMARY OF EMPLOYEE CONCERNS
UNCONTROLLED TENSION

EC #	SUMMARY
IN-85-433-002	THE CABLE ON UNIT 1&2 HAS BEEN PULLED SO HARD (MANUALLY NOT MECHANICALLY) THAT THE INSULATION SLIPS OR BREAKS. THE CABLE THAT BREAKS IS CORRECTED BUT THE DAMAGED CABLE IS IGNORED AND LEFT FOR THE MEGGER TEST TO DETERMINE DAMAGE.
IN-85-436-004	CONDUIT OVERFILLED. PULL TENSION WAS NOT MONITORED.
IN-85-527-001	AN A-TRAIN CABLE WAS PULLED WITHOUT A FUSE-LINK. SUPERVISOR SAID TO SIGN OFF QC INSPECTOR SO THE WIRE COULD BE CUT EVEN.
IN-85-774-006	CABLE WAS PULLED UTILIZING A "COME ALONG".
IN-85-856-005	THE PRACTICE TO USING BREAK ROPES WHEN PULLING CABLES DID NOT BECOME EFFECTIVE UNTIL 1984. ALL THE "BIG" PULLS OCCURED 3+YEARS AGO WITHOUT BREAK ROPE.
IN-85-978-001	CABLES WERE PULLED USING CHERRY-PICKER CRANES AND MACK TRUCKS.

SUMMARY OF EMPLOYEE CONCERNS
UNCONTROLLED TENSION

EC #	SUMMARY
IN-85-993-006	NOT ALL ELECTRICAL INSPECTION SHEETS PROVIDE OBJECTIVE EVIDENCE THAT ELECTRICAL CABLE SIDE WALL TENSION MAXIMUM VALUES WERE NOT EXCEEDED DURING PULLING.
IN-86-028-001	CABLE PULL LIMITS WERE EXCEEDED ON THE CABLE GOING TO THE INTAKE PUMPING STRUCTURE ELECTRICAL MANHOLES.
IN-86-199-001	CABLES PULL ARE NOT ALWAYS PERFORMED TO THE REQUIREMENTS OF QCI. BREAK LINKS WERE NOT USED DURING CABLES PULLS.
IN-86-201-001	CABLE PULLING LIMITS MAY HAVE BEEN EXCEEDED DURING CABLE PULLS BEFORE 1982
IN-86-212-001	CABLE PULL LIMITS HAVE BEEN EXCEEDED IN UNITS 1&2.
IN-86-254-002	CABLE BREAK LINKS WERE NOT USED PRIOR TO 1984. CABLE MAY HAVE BEEN DAMAGED.

SUMMARY OF EMPLOYEE CONCERNS
UNCONTROLLED TENSION

EC #	SUMMARY
IN-86-259-001	TVA FAILED TO USE FUSE LINKS OR OTHER TENSION INDICATORS WHILE PULLING CABLES.
IN-86-259-002	CONSTRUCTION ATTACHED A STEEL CABLE BEFORE AND AFTER THE FUSE LINKS. FUSE LINKS WERE NOT USED TO PREVENT CABLE DAMAGE DURING CABLE PULLS, AND CABLES WERE DAMAGED OR BROKEN.
IN-86-259-004	CABLES HAVE BEEN PULLED BY USING A COME-A-LONG WINCH. DOORS ARE HELD SHUT TO PREVENT QC OBSERVATION.
IN-86-259-014	CABLE BROKE DUE TO IMPROPER PULLING METHODS. CABLE WAS THEN SPLICED AND PULLED INTO CONDUIT.
IN-86-262-003	APPROXIMATELY 1 1/2 YRS. AGO, A BREAK LINK WAS TO BE USED DURING CABLE PULL; HOWEVER A "STEEL CHOKER" IS STILL BEING ADDED AND THE PROBABILITY OF EXCEEDING THE MAXIMUM PULL TENSION IS VERY HIGH
IN-86-266-001	CABLE PULLING HAS BEEN ACCOMPLISHED BY TRUCKS AND WINCHES.

SUMMARY OF EMPLOYEE CONCERNS
UNCONTROLLED TENSION

EC #	SUMMARY
IN-86-266-002	MANY CABLES WERE PULLED WITHOUT USING FUSE LINKS.
IN-86-314-001	COMMON PRACTICE TO UTILIZE IMPROPER CABLE PULLING TECHNIQUES (WINCHES AND HAND COME-ALONGS).