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WIPS—Computer Code for Whip and Impact Analysis of Piping Systems

Summary Report

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Prepared for
U.S. Nuclear Regulatory Commission

Lawrence
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Laboratory

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1. INTRODUCTION

WIPS (Whip and Impact of Piping Systems) is a special purpose computer code for the structural analysis of pipe whip dynamic effects following a postulated pipe rupture. WIPS has been developed primarily to provide support for the pipe whip analysis procedures described in Section 3.6.2 of the U.S. Nuclear Regulatory Commission Standard Review Plan [1].

This report summarizes the purpose and scope of the WIPS development effort, identifying those clauses in the Standard Review Plan which refer to pipe whip analysis, and indicating how the WIPS code can be used to provide supporting data. Detailed information on use of the code is contained in accompanying reports which cover (1) user instructions [2], (2) theory [3], (3) programming procedures [4], and (4) verification examples [5].

2. PURPOSE AND SCOPE

2.1 STANDARD REVIEW PLAN EXCERPTS

The following excerpts from Standard Review Plan, Section 3.6.2, relate to the purpose of the WIPS code.

(1) Page 3.6.2-1: At the construction permit (CP) stage, the staff review covers . . . the dynamic analysis methods used to verify the integrity and operability of mechanical components, component supports, and piping systems, including restraints and other protective devices, under postulated pipe rupture loads.

(2) Page 3.6 2-2: At the operating license (OL) stage, the staff review covers . . . the acceptability of the analysis results, including the jet thrust and impingement forcing functions and pipe whip dynamic effects . . .

(3) Page 3.6.2-4: Analyses of pipe motion caused by the dynamic effects of postulated failures are reviewed. These analyses should show that pipe motions will not be such as to result in unacceptable impact upon, or overstress of, any structure, system, or component important to safety to the extent that essential functions would be impaired or precluded. The analysis methods used should be adequate to determine the resulting loadings in terms of the kinetic energy or momentum induced by the impact of the whipping pipe, if unrestrained, upon a protective barrier or a component important to safety and to determine the dynamic response of the restraints induced by the impact and rebound, if any, of the ruptured pipe.

(4) Page 3.6.2-4: An unrestrained whipping pipe should be considered capable of causing circumferential and longitudinal breaks, individually, in impacted pipes of smaller nominal pipe size, and developing through-wall cracks in equal or larger nominal pipe sizes with thinner wall thickness, except where analytical or experimental, or both, data for the expected range of impact energies demonstrate the capability to withstand the impact without rupture.

(5) Page 3.6.2-4: An analysis of the dynamic response of the pipe run or branch should be performed for each longitudinal and circumferential postulated piping break.

(6) Page 3.6.2-4: Dynamic analysis methods used for calculating piping and restraint system responses to the jet thrust developed following the postulated rupture should adequately account for the following effects: (a) mass inertia and stiffness properties of the system, (b) impact and rebound, (c) elastic and inelastic deformation of piping and restraints, and (d) support boundary conditions.

(7) Page 3.6.2-4: . . the allowable capacity of crushable material shall be limited to 80% of its rated energy dissipating capacity . . . pure tension members shall be limited to an

allowable strain of 50% of the ultimate uniform strain . . . (or) . . . the strain associated with 50% of the uniform energy absorption capacity . . . the method of dynamic analysis used should be capable of determining the inelastic behavior of the piping and restraint system within these design limits.

(8) Page 3.6.2-6: A 10% increase of minimum specified design yield strength may be used in the analysis to account for strain rate effects.

(9) Page 3.6.2-6: Dynamic analysis methods and procedures presented should include:

(1) A representative mathematical model of the piping system or piping and restraint system.

(2) The analytical method of solution selected.

(3) Solutions for the most severe responses among the piping breaks analyzed.

(4) Solutions with demonstrable accuracy or justifiable conservatism.

The extent of mathematical modeling and analysis should be governed by the method of analysis selected.

(10) Page 3.6.2-6: Acceptable (dynamic analysis) models . . . include the following:

(1) Lumped Parameter Analysis Model: Lumped mass points are interconnected by springs to take into account inertia and stiffness properties of the system, and time histories of responses are computed by numerical integration, taking into account clearances at restraints and inelastic effects. In the calculation, the maximum possible initial clearance should be used to account for the most adverse dynamic effects of pipe whip.

(2) Energy Balance Analysis Model: Kinetic energy generated during the first quarter cycle movement of the rupture pipe and imparted to the piping and restraint system through impact is converted into equivalent strain energy. In the calculation, the maximum possible initial clearance at restraints should be used to account for the most adverse dynamic effects of pipe whip. Deformations of the pipe and the restraint should be compatible with the level of absorbed energy. The energy absorbed by the pipe deformation may be deducted from the total energy imparted to the system. For applications where pipe rebound may occur upon impact on the restraint, an amplification factor of 1.1 should be used to establish the magnitude of the forcing function in order to determine the maximum reaction force of the restraint beyond the first quarter cycle of response. Amplification factors other than 1.1 may be used if justified by more detailed dynamic analysis.

(3) Static Analysis Model: The jet thrust force is represented by a conservatively amplified static loading,

and the ruptured system is analyzed statically. An amplification factor can be used to establish the magnitude of the forcing function. However, the factor should be based on a conservative value obtained by comparison with factors derived from detailed dynamic analyses performed on comparable systems.

(4) Other models may be considered if justified.

(11) Page 3.6.2-7: The time-dependent function representing the thrust force caused by jet flow from a postulated pipe break or crack should include the combined effects of the following: the thrust pulse resulting from the sudden pressure drop at the initial moment of pipe rupture; the thrust transient resulting from wave propagation and reflection; and the blowdown thrust resulting from build-up of the discharge flow rate, which may reach steady state if there is a fluid energy reservoir having sufficient capacity to develop a steady jet for a significant interval. Alternatively, a steady state jet thrust function may be used . . . if the energy balance model or the static model is used in the subsequent pipe motion analysis. The function should have a magnitude not less than:

$$T = KpA$$

where

p = system pressure prior to pipe break;

A = pipe break area; and,

K = thrust coefficient.

(12) Page 3.6.2-7: Analyses of jet impingement forces are reviewed. These analyses should show that jet impingement loadings on nearby safety-related structures, systems, and components will not be such as to impair or preclude essential functions.

(13) Page 3.6.2-17: (For circumferential breaks) pipe whipping should be assumed to occur in the plane defined by the piping geometry and configuration, and to initiate pipe movement in the direction of the jet reaction.

(14) Page 3.6.2-17: Longitudinal breaks should be assumed to result in an axial split without pipe severance. Splits should be oriented (but not concurrently) at two diametrically-opposed points on the piping circumference such that the jet reaction causes out-of-plane bending of the piping configuration. Alternatively, a single split may be assumed at the section of highest tensile stress as determined by detailed stress analysis (e.g., finite element analysis).

(15) Page 3.6.2-16: (For longitudinal breaks) piping movement should be assumed to occur in the direction of the jet reaction unless limited by structural members, piping restraints, or piping stiffness as demonstrated by inelastic limit analysis.

2.2 WIPS CAPABILITIES

2.2.1 WIPS Modules

WIPS is not a single computer program, but a series of sixteen program modules which share a common data base and are linked by an executive program (WIPS-EXEC). Twelve of the modules assist the WIPS user to prepare input data, one module (the largest and most complex) performs dynamic response analysis, and the last three assist the user to process the analysis results. The analysis module (WIPS-ANAL) is a sophisticated structural analysis code, based essentially on the "lumped parameter analysis model" as defined in Excerpt 10 of the preceding section. WIPS-ANAL can, if desired, be run as a stand-alone code. For pipe whip applications, however, it is much more efficient, in terms of man-hours, to use the WIPS input modules to prepare the input data, and to run WIPS-ANAL under the control of WIPS-EXEC.

2.2.2 Analysis Options

WIPS can perform dynamic pipe whip analyses of three different types, which can be identified as: (1) restrained pipe analyses; (2) unrestrained pipe analyses; and (3) contact analyses.

A restrained pipe analysis will usually be appropriate if the pipe is prevented from large whipping motions by whip restraints located near the break. The dynamic displacements of the pipe will then usually be small, and a small displacements analysis is appropriate. Both the piping and the restraints will generally respond inelastically. However, the amount of inelastic deformation of the pipe will usually be small, and the main concern in the analysis is prediction of the stresses and strains in the pipe whip restraints. It will usually be appropriate to model the pipe as a series of beam-type elements, ignoring the possibility of pipe wall buckling.

An unrestrained pipe analysis will be appropriate if the pipe is not closely restrained, so that large whipping motions can occur. In this case, a large displacements analysis is necessary, with larger inelastic deformations of the piping components. If local buckling of the pipe wall can be assumed not to occur (or not to be significant), the pipe can be modeled as a series of beam-type elements. However, if local buckling is potentially important, it may be necessary to model certain pipe components as assemblages of shell finite elements. WIPS allows this type of finite element model, but the computational cost is greatly increased compared with a model using only beam-type elements.

An unrestrained analysis can predict the path swept out by the jet, and the location and velocity of the pipe at impact with walls or other structures. With this type of analysis it is also possible to analyze the post-impact behavior, by modeling the impacted structure as a series of stiff springs (gap elements). It must be recognized, however, that impact force magnitudes depend greatly on the stiffnesses and masses of the impacting bodies, being theoretically infinite for rigid impact. Hence, impact forces calculated using beam-type elements for the pipe are likely to be inaccurate, because local deformations of the pipe wall are ignored. For an accurate assessment of local impact effects, it will usually be necessary to perform a contact analysis.

In a WIPS contact analysis, piping components are modeled using shell finite elements, and calculations are performed to determine whether one finite element mesh makes contact with another. If so, contact forces (normal and friction) are calculated to prevent overlap. Hence, detailed information on overall pipe motion, local pipe deformation, and contact forces can be obtained. In the current version of WIPS, input modules are available only for straight pipe, elbow and flat plate meshes, although the WIPS-ANAL module has the capability to consider contacting meshes of essentially arbitrary shape. It must be noted, however, that contact analyses can be extremely costly.

2.2.3 WIPS Elements

The WIPS-ANAL analysis module consists of a "base" program plus a library of elements. New elements can be added relatively easily (recognizing that the programming for a nonlinear element is never simple in absolute terms). At present, five different elements may be specified, as follows.

(1) A beam-type element with inelastic properties defined in terms of total cross-section actions (axial force, bending moment, and torsional moment) and corresponding deformations. Either a small displacements or a large displacements option may be selected. Only straight elements may be specified. Strain rate effects may be taken into account, if desired. This element is computational efficient, but requires a significant amount of preliminary calculation to determine the action-deformation relationships.

(2) A beam-type element of pipe cross section, with inelastic properties defined in terms of a stress-strain relationship. Elements may be straight or curved. For curved elements, cross section ovalling is taken into account by a semi-rational procedure. Either small or large displacements may be considered, and strain rate effects may be taken into account. The effects of internal pressure on yield and cross-section ovalling are considered. The element requires no preliminary calculation, but is more expensive computationally than the preceding element.

(3) A pipe whip restraint element which is intended mainly for modeling U-bar restraints, but which can also be used for restraints of other types. The restraint is modeled essentially as an inelastic bar acting in tension, with provision for large displacements and strain rate effects.

(4) A gap-friction element, which allows unrestricted motion until the gap closes, and then provides resistance normal and tangential to a restraint plane. If the tangential force exceeds the friction resistance (current normal force multiplied by a friction coefficient), tangential slip occurs.

(5) A shell element, for detailed modeling of pipe components. Large displacements, yielding and strain rate effects may be considered. WIPS input modules are available for automatic generation of finite element meshes for straight pipe and elbow components and for flat plates.

All of the elements allow for three-dimensional dynamic response. For cases where the response is known to be only two-dimensional, this may be specified (the computational effort is reduced).

2.2.4 Existing Codes with Pipe Whip Capability

A number of proprietary pipe whip codes are in use for the design of pipe whip restraints. These codes are typically limited to small displacements analyses of restrained piping. A number of general purpose structural analysis codes (for example, ABAQUS, ADINA, and ANSYS) have the capability to perform pipe whip analyses, including both small displacements analysis for restrained piping and large displacements analysis for unrestrained piping. Such codes may have the ability to model piping components using shell finite elements as well as beam-type elements. However, the data preparation effort for such models is likely to be a formidable task. None of the available codes appears to have the ability to perform surface-to-surface contact analyses.

The advantages of WIPS in comparison with the existing codes are as follows:

(1) WIPS contains interactive input modules which greatly reduce the man-hours required to develop and check the input data. The savings are particularly dramatic if shell finite element meshes are used.

(2) The WIPS-ANAL analysis module is a general purpose structural analysis code with capabilities which are available in few, if any, other codes. These capabilities include a multilevel substructuring, general nodal displacement slaving, a flexible data management system, and surface-to-surface contact computations.

(3) The WIPS elements are more sophisticated than those available in most other codes. This permits more precise modeling.

(4) The WIPS-ANAL solution strategy is substantially automatic, and requires relatively little skill on the part of the analyst. In particular, the time step is automatically varied during the step-by-step dynamic analysis. Other codes (except ABAQUS) require a constant time step, which can be difficult to select.

(5) WIPS includes an interactive results post-processing module which can greatly reduce the effort required to produce tabulated and plotted results.

2.3 SUPPORT FOR STANDARD REVIEW PLAN

2.3.1 Grouping of SRP Excerpts

Fifteen pertinent excerpts from the Standard Review Plan were listed in Section 2.1 of this report. These excerpts can be divided into three groups, as follows.

(1) General Requirements: Excerpts 1, 2, 3, 5, 6, 9, 12, and 14.

(2) Acceptable Analysis Procedures: Excerpts 8, 10, 11, 13, and 15.

(3) Specific Design Assumptions: Excerpts 4 and 7.

2.3.2 Role of WIPS

Possible applications of WIPS in direct support of the Standard Review Plan are as follows.

(1) Determining the adequacy of the Energy Balance Analysis and Static Analysis models (Excerpt 10).

(2) Determining the adequacy of the 10% strength increase for strain rate effects (Excerpt 8).

(3) Identifying cases in which the assumption of two-dimensional motion is reasonable, and cases in which three-dimensional motion should be considered (Excerpts 13 and 15).

(4) Assisting to determine the adequacy of the rule in Excerpt 4, concerning breaks following pipe-to-pipe impact.

Other possible applications of WIPS for support of regulatory activities are as follows.

(1) Confirmation of Architect-Engineer pipe whip computations (Excerpts 6 and 7).

(2) Analysis of the motion of unrestrained pipe, and the corresponding path traced out by the jet, to study whether jet impingement occurs on safety-related targets (Excerpt 12).

(3) Performance of parameter studies on typical configurations, to develop charts for use in design or design review.

(4) Investigation of local pipe damage following pipe-to-wall impact.

(5) Investigation of structural vibration effects in piping remote from the break during pipe whip (e.g. support loads and valve accelerations).

3. REFERENCES

1. U.S. Nuclear Regulatory Commission Standard Review Plan, NUREG-0800, 1981 (formerly NUREG-75/087, 1975).

2. WIPS: Computer Code for Whip and Impact Analysis of Piping Systems: Part A: User's Manual.

3. WIPS: Computer Code for Whip and Impact Analysis of Piping Systems: Part B: Theory Manual.

4. WIPS: Computer Code for Whip and Impact Analysis of Piping Systems: Part C: Programmer's Manual.

5. WIPS: Computer Code for Whip and Impact Analysis of Piping Systems: Part D: Verification Examples.

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This report summarizes the purpose and scope of the WIPS development effort, identifying those clauses in the standard Review Plan which refer to pipe whip analysis, and indicating how the WIPS code can be used to provide supporting data. Detailed information on use of the code is contained in accompanying reports which cover (1) use instructions, (2) theory, (3) programming procedures, and (4) verification examples.

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