XLPR MODELS SUBGROUP REPORT

CYCLIC STRESS INTENSITY FACTORS

PROBABILISTIC FRACTURE MECHANICS CODE

DISCLAIMER

xLPR Models Subgroup Report

Cyclic Stress Intensity Factors

xLPR-MSGR-TIFF Version 1.0	
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EXECUTIVE SUMMARY

TIFFANY is a standalone module that prepares inputs to xLPR related to cyclic conditions arising from temperature and pressure excursions of the reactor coolant. These inputs, the cyclic stress intensity factors and the related information, are used in fatigue crack initiation and growth calculations performed by xLPR.

Excursions of the coolant temperature in nuclear power reactors produce stresses within the walls of the pressure vessel and piping. These stresses are a result of the temperature gradients produced and are referred to as radial gradient thermal stresses. Coolant temperature changes are therefore a source of cyclic stress that can be an important contributor to fatigue crack growth.

The necessary information for calculation of the cyclic stress intensity factors due to coolant temperature excursions is typically the temperature-time history of the coolant. From this, it is necessary to determine the history of the radial variation of temperature within the pipe wall. The ability to treat the heat conduction aspect of the problem is required to be contained within the code using the resulting temperature field to calculate the stresses. This is accomplished by use of relationships derived from elasticity theory for axisymmetric bodies subject to axisymmetric temperature fields. Once the stresses are known, the resulting stress intensity factors for semi-elliptical cracks in the inside pipe surface are evaluated by the use of influence functions. Axial and circumferential cracks are treated. The cyclic stress intensity factors (ΔK) are found from the temporal variation of K. Important additional features of the code include consideration of convective heat transfer and the ability to include the influences of cladding, inlays or overlays on both the temperature fields and stresses.

The TIFFANY module is called by a pre-processor which prepares the inputs for xLPR by managing input and output of TIFFANY.

The design, development and testing of the module is described in the corresponding Software Requirements Description (SRD), Software Design Description (SDD), Software Test Plan (STP) and Software Test Results Report (STRR) [3, 11, 12, 4] documents. The module validation is reported in the Module Validation Report (MVR) [10] document.

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NOMENCLATURE/LIST OF SYMBOLS

a	Crack depth
c	Half crack length
csp	Specific heat
E	Elastic modulus
H1	Inner pipe thickness (in case of overlay or clad piping)
h2	Outer pipe thickness (in case of overlay or clad piping)
K	Stress intensity factor
r	Radial coordinate
r_i	Inside radius
r_o	Outside radius
r_c	Interface radius
t	Time
T	Temperature
α	Coefficient of thermal expansion
ΔK	Cyclic stress intensity factor
Δp	Deviation from the operating pressure
K	Thermal conductivity
ρ	Density
θ	Angular location
σ_T	Global membrane stress
σ_B	Global bending stress
μ	Poisson’s Ratio

ACRONYMS AND INITIALISMS

DLL	Dynamic Link Library
DMW	Dissimilar Metal Weld
FE	Finite Element
FEA	Finite Element Analysis
EPRI	Electric Power Research Institute
MVR	Module Validation Report
NRC	Nuclear Regulatory Commission
PWC	Part-Wall Crack
RTM	Requirements Traceability Matrix
SDD	Software Design Description
SI	Système International d'Unités
SRD	Software Requirements Document
STP	Software Test Plan
STRR	Software Test Results Report
TWC	Through-Wall Crack
V&V	Verification and Validation
xLPR	eXtremely Low Probability of Rupture

1. INTRODUCTION

1.1 Subgroup Roles & Responsibilities

The xLPR-TIFFANY Subgroup is responsible for developing the model for computing cyclic stress intensity factors due to plant transients and user-specified minimum/maximum stresses, as functions of crack size. Related information, such as transient rise-time and cyclic stress at the pipe inner surface, is also generated. Output for each transient is generated by xLPR-TIFFANY that is then used as inputs to xLPR for analysis of fatigue crack initiation and growth.

TIFFANY is strictly a deterministic module. Any uncertainties associated with a TIFFANY analysis are in the inputs, primarily in the time-temperature inputs. Treatment of such uncertainties is beyond the scope of the TIFFANY module and are treated elsewhere. The material properties that enter into TIFFANY evaluations (coefficient of thermal expansion, thermal conductivity, etc.) are well defined.

The subgroup ensured incorporation of the best-estimate models currently available for modeling cyclic stress intensity factors, cyclic stresses and transient rise-times into the TIFFANY xLPR Module source code. The subgroup was also responsible for providing test cases for use in verifying and validating the computation of cyclic stress intensity factors and related information, and then performing the verification and validation of the TIFFANY calculated results.

1.2 Subgroup Objectives

The primary objectives of the TIFFANY Subgroup were to:

- Define the best-estimate analytical model for computation of cyclic stress intensity factors due to pressure and thermal excursions of reactor primary coolant.
- Define procedures for extraction of related results, including: cyclic stress at inner surface of the pipe; rise time of transient, and changes in restraint of thermal expansion stress.
- Develop the associated software code to perform the calculations.
- Define, perform and document the necessary test cases for use in verifying and validating TIFFANY model performance.
- Produce TIFFANY model documentation.
- Interface with the xLPR Computational Group to ensure proper performance and integration of the TIFFANY module.

1.3 Models Under Auspices of Subgroup

The TIFFANY Subgroup provided models for the computation of cyclic stress intensity factors (and related cyclic data) due to plant operating transients. This involved development of models for computation of transient temperature fields, which are then used in the computation of transient stresses. The xLPR stress intensity factor (K) modules [1,2] are then accessed to compute stress intensity factors, and results are sorted to define maximum and minimum values of the stress intensity factor for a specified set of crack sizes and orientations.

2. TIFFANY MODEL DESCRIPTION

TIFFANY is a stand-alone module for evaluation of cyclic stress intensity factors due to temperature excursions as functions of crack size for axial and circumferential cracks in a single or bimaterial pipe (such as pipe with an overlay)..

Excursions of the coolant temperature in nuclear power reactors produce stresses within the walls of the pressure vessel and piping. These stresses are a result of the temperature gradients produced and are referred to as radial gradient thermal stresses. Coolant temperature changes are therefore a source of cyclic stress that can be an important contributor to fatigue crack growth.

The necessary information for calculation of the cyclic stress intensity factors due to coolant temperature excursions is typically the temperature-time history of the coolant. From this, it is necessary to determine the history of the radial variation of temperature within the pipe wall. The ability to treat the heat conduction aspect of the problem is required to be contained within the code using the resulting temperature field to calculate the stresses. This is accomplished by use of relationships derived from elasticity theory for axisymmetric bodies subject to axisymmetric temperature fields. Once the stresses are known, the resulting stress intensity factors for semi-elliptical cracks in the inside pipe surface are evaluated by the use of influence functions. Axial and circumferential cracks are treated. The cyclic stress intensity factors (ΔK) are found from the temporal variation of K. Important additional features of the code include consideration of convective heat transfer and the ability to include the influences of cladding, inlays or overlays on both the temperature fields and stresses.

2.1 Model requirements for xLPR

TIFFANY is a stand alone module that prepares inputs to xLPR related to cyclic conditions arising from temperature and pressure excursions of the reactor coolant. These inputs are used in fatigue crack initiation and growth calculations performed by xLPR.

2.2 Model Development

FIgure 1, which is from the TIFFANY Software Requirements Document (SRD) [3], summarizes the components of the analysis performed by the TIFFANY module for xLPR Version 2.

As depicted in Figure 1, TIFFANY is capable of analyzing a pipe composed of two materials (with thicknesses h1 and h2), such as encountered in overlay or clad piping. Fluid properties for liquid water are temperature-dependent and are described in Reference [4].

The outputs from a TIFFANY analysis are used as inputs to xLPR. A TIFFANY analysis must be performed for each thermal transient in the fatigue history being analyzed by xLPR, with a separate set of inputs to describe each transient.

2.3 Basis for Selection

Computation of the changes in cyclic stress intensity factors (ΔK) due to temperature excursions and other loadings can be accomplished by a variety of means, including procedures ranging in complexity up to three-dimensional finite element analysis with cracks included in the model. The approach in TIFFANY was selected for its simplicity and speed of computation, plus its maximum use of software that was already available [5]. There is no sacrifice in accuracy, other than TIFFANY's restriction to straight sections of pipe.

2.4 Mathematical Description of Model

As Figure 1 shows, the TIFFANYanalysis for a given transient is composed of many discreet steps:

(1). computation of the transient temperature field,

(2). computation of thermal stresses due to the radial gradient of the transient temperature field,

(3). other loadings and related computations of the cyclic stress at the inner surface, the rise-time of the transient, contributions of changes in the average pipe wall temperature to the restraint of thermal expansion stress, and contributions of pressure excursions and stratification and mechanical loading during the transient,

(4). computation of stress intensity factors and their changes for various crack sizes and orientation due to the stresses in steps 3 and 4,

(5). sorting of the stress intensity factors to obtain the maximum and minimum changes for a given crack size and orientation.

The mathematical description of each of these steps is detailed in the the related TIFFANY module documentation, primarily the TIFFANY SRD [3]. Each of these steps will be briefly summarized here.

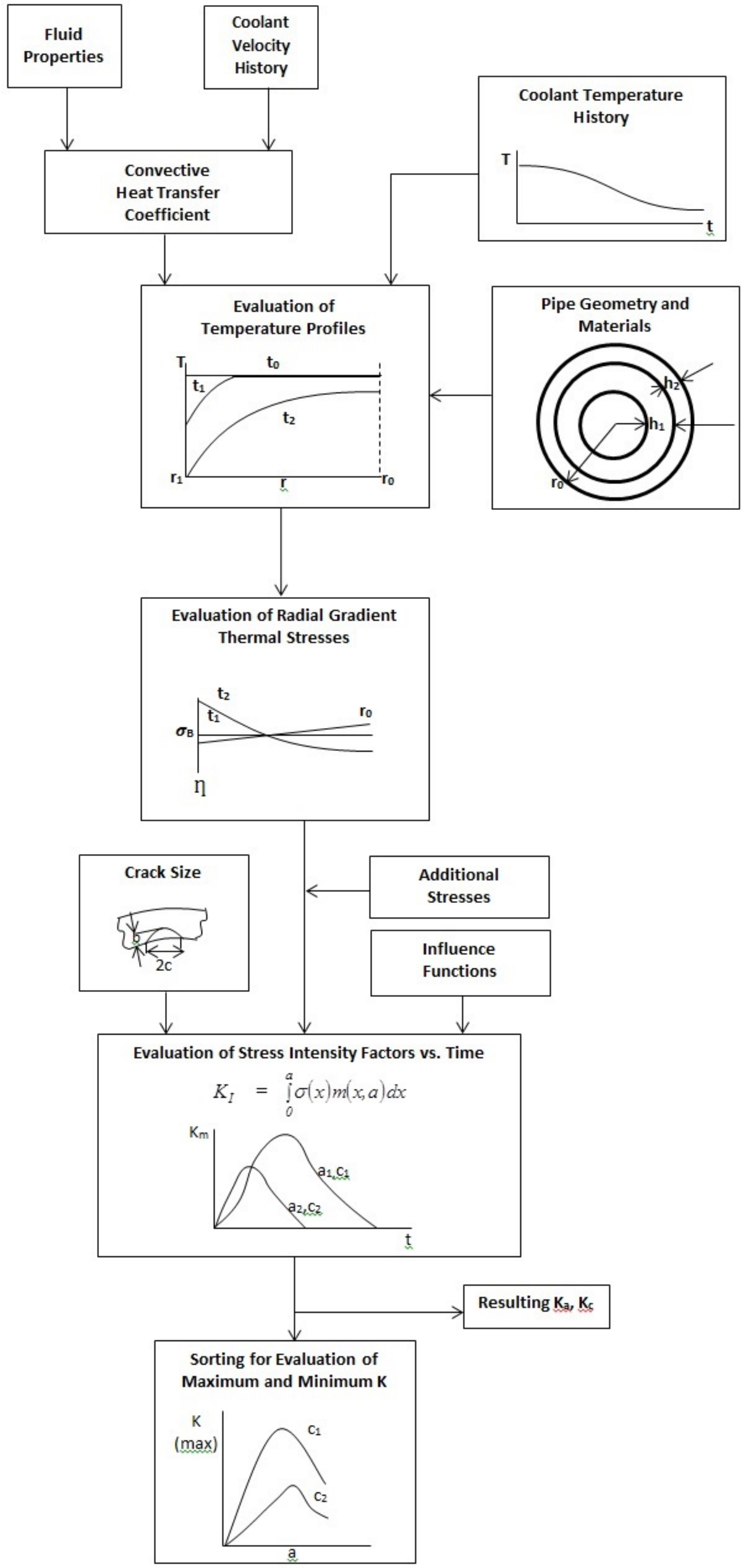

Figure 1. Components of xLPR-TIFFANY Computer Code and their Interrelationships.

2.4.1 Assumptions

The usual assumptions of linear elasticity and classical heat conduction are made in the TIFFANY analysis. The thermophysical properties are taken to be independent of temperatuare, other than a linear variation with temperature of the thermal conductivity. The thermal and elasticity analysis assumes a long circular cylinder with axisymmetric boundary conditions. Plane cross-sections remain plane and there is no net axial force due to the radial temperature gradient. The stress intensity factor solutions employed to obtain K from the stresses are also for long circular cylinders. Hence, TIFFANY results are strictly applicable only to long sections of pipe. They are assumed to be applicable to other piping components, such as elbows, tees and nozzles.

Assumption	Technical Basis	Expected Impact on Module Bias and Uncertainty
assumptions of linear elasticity and classical heat conduction	The use of linear elastic behavior is conservative, as the effects of through-wall thermal gradients and pressure driven stresses are impacted by the highly constrained material behavior, as all of the strain is elastic in nature. This prevents significant, and potentially advantageous stress redistribution, which would normally occur in an inelastic material environment, which could result in reduced stresses or limit the maximum stresses. The use of classical heat conduction assumes no phase transformation, which would invalidate the physical assumptions of classic heat conduction relationship. The exclusion of radiation and convection heat transfer behavior is reasonable, as the typical operating temperatures in nuclear piping components are insufficient to generate significant radiant heat transfer behavior, and convection heat transfer is only significant at material surfaces, which are already captured.	No bias or uncertainty expected.
thermophysical properties are taken to be independent of temperatuare	These properties vary minimally with temperature	May result in some bias with temperature but the impact is expected to be minimal
thermal and elasticity analysis assumes a long circular cylinder with axisymmetric boundary conditions	Assumption simplifies the problem to one with a readily tractable & reliable solution	Minimal impact expected

Assumption	Technical Basis	Expected Impact on Module Bias and Uncertainty
Plane cross-sections remain plane and there is no net axial force due to the radial temperature gradient	Simplifying assumption that does not take into account the effects of variation in thermal expansion of the different materials in DMWs. These differences may be small (?).	Minimal impact expected
the effective elastic modulus, E, is calculated as a weighted average of the cross-sectional areas and elastic modulus values for the inner and outer material	Simplifying assumption calculated using a rule-of-mixtures type of relationship but this does not account for the stresses arising due to the dissimilar elastic modulii. The structural behavior of radial bi-metallic material is simulated by using a single constant value of E and μ. However, these values are 'weighted,' based on the cross-sectional areas of the two bimetallic materials. Therefore, bimetallic structures with a relatively small ratio of bimetallic material, will behave more strongly like the majority material. In addition, the variation of E and μ between typical steel materials is relatively small when compared to the variation of μ, thermal conductivity and diffusivity.	Minimal impact expected

2.4.2 Temperature Field

The temperature field in the pipe is assumed to be independent of distance along the pipe and to be axisymmetric. This is consistent with the usual treatment of radial gradient thermal stresses in pipes [6]. The temperature field is therefore a function of radial coordinate and time only, T(r, t). The one-dimensional heat conduction problem is very amenable to a numerical procedure, and such an approach is therefore used. Consideration of temperature-dependent material properties, such as thermal conductivity, is straightforward in the numerical procedures. The thermal conductivity can be temperature-dependent in xLPR-TIFFANY.

The following is the governing partial differential equation for the conduction of heat in the pipe wall under the idealized conditions mentioned above.

$$\rho c_{sp} \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r}\left(kr \frac{\partial T}{\partial r} \right) \qquad \text{(Eqn.1)}$$

In the general case, the material properties k, c_{sp} and ρ (thermal conductivity, specific heat and density) can be functions of temperature.

A convection heat transfer boundary condition is applied at the inner surface of the pipe. The correlation provided in Edwards [7] (page 166), as described in theTIFFANY SRD [3], is incorporated into TIFFANY to define the convection heat transfer coefficient knowing the coolant flow velocity and temperature. An insulated boundary condition is applied at the outer surface of the pipe.

A numerical procedure for evaluation of the temperature in the pipe wall is employed. This is accomplished by employing a finite difference procedure that utilizes second order correct differing of the diffusion term (i.e., spatial variation) and first order correct backward differing of the temporal term. This leads to equations such as

$$\frac{\delta^2 h^2 \rho c_{sp}}{\Delta t}(T_j - T^*_j) = \frac{1}{r_j}\left[T_{j+1}(k_{j+1}r_{j+1} + k_j r_j) - T_j(k_{j+1}r_{j+1} + 2k_j r_j + k_{j-1}r_{j-1}) + T_{j-1}(k_j r_j + k_{j-1}r_{j-1})\right]$$

(Eqn. 2)

The "*j*" subscript refers to conditions at the "*j*-th" node. The "*" superscript refers to conditions at the previous time-step. δ is the dimensionless nodal spacing, which equals [1/number of spatial increments in the material 1]=[1/number of spatial increments in material 2]. *h* is the total pipe wall thickness.

Equation 2, along with analogous formulations of the boundary conditions (and continuity conditions at the material interface if cladding, inlay or overlay is considered), lead to a set of simultaneous equations for the current nodal temperature in terms of material properties, geometrical terms and temperature from the previous time-step. These equations are readily and efficiently solved by the method of successive substitutions.

2.4.3 Thermal Stresses

The stresses in the pipe wall are evaluated by use of elasticity theory from the transient temperature field determined by the finite difference procedure described in Section 2.4.2. The idealization of only radial variations of the stresses and displacements leads to a particularly simple one dimensional quasi-static elasticity problem. Such problems are discussed in Ref. [8], and the case of interest here of a single material is treated in Section 135 of that reference. The discussion in Ref. [8] can easily be generalized to provide results for a bimaterial pipe. The treatment here will be for the two materials to have the same elastic constants E and μ (E can be weighted to get an equivalent value, see Equation 6), but different coefficients of thermal expansion α. The structural behavior of radial bi-metallic material is simulated by using a single constant value of E and μ. However, these values are 'weighted,' based on the cross-sectional areas of the two bimetallic materials. Therefore, bimetallic structures with a relatively small ratio of bimetallic material, will behave more strongly like the majority material. In addition, the variation of E and μ between typical steel materials is relatively small when compared to the variation of μ, thermal conductivity and diffusivity. The axial strain, εz, is taken to be constant (not zero) at any instant, and equal to a value that produces a zero net axial load. This is consistent with the usual treatment of radial gradient thermal stresses in piping [6,8]. This condition, along with the boundary condition of zero radial stress at the inner and outer pipe wall and continuity of displacements and radial stress at the bimaterial interface, allows the following end results to be obtained. (Refer to Figure 2 for the notation employed.)

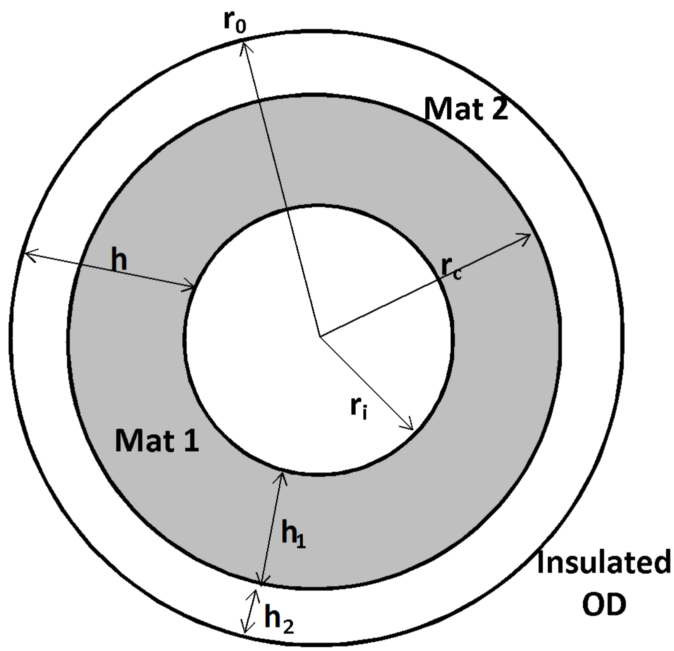

Figure 2. Cross-section of a clad pipe or with an inlay or overlay.

In region 1 (inner material)

$$\sigma_r = \frac{E}{1-\mu}\frac{1}{r^2}\left\{-\alpha_1\int_{r_i}^{r} r(T-T_0)dr + \frac{r^2-r_i^2}{r_o^2-r_i^2}\Omega\right\} \quad \text{(Eqn. 3a)}$$

$$\sigma_\theta = \frac{E}{1-\mu}\frac{1}{r^2}\left\{\alpha_1\int_{r_i}^{r} r(T-T_0)dr - \alpha_1 r^2(T-T_0) + \frac{r^2+r_i^2}{r_o^2-r_i^2}\Omega\right\} \quad \text{(Eqn. 3b)}$$

$$\sigma_z = \frac{E}{1-\mu}\left\{\frac{2}{r_o^2-r_i^2}\Omega - \alpha_1(T-T_0)\right\} \quad \text{(Eqn. 3c)}$$

where

$$\Omega = \alpha_1\int_{r_i}^{r_c} r(T-T_0)dr + \alpha_2\int_{r_c}^{r_o} r(T-T_o)dr \quad \text{(Eqn. 4)}$$

In region 2 (outer material)

$$\sigma_r = \frac{E}{1-\mu}\frac{1}{r^2}\left\{-\alpha_2\int_{r_c}^{r} r(T-T_0)dr - \frac{r_o^2-r^2}{r_o^2-r_i^2}\alpha_1\int_{r_1}^{r_c} r(T-T_o)dr + \frac{r^2-r_i^2}{r_o^2-r_i^2}\alpha_2\int_{r_c}^{r_o} r(T-T_o)dr\right\}$$

(Eqn. 5a)

$$\sigma_\theta = \frac{E}{1-\mu}\frac{1}{r^2}\left\{\alpha_2\int_{r_c}^{r} r(T-T_0)dr - \alpha_2 r^2(T-T_0) + \frac{r^2+r_o^2}{r_o^2-r_i^2}\alpha_1\int_{r_i}^{r_c} r(T-T_0)dr + \frac{r^2+r_i^2}{r_o^2-r_i^2}\alpha_2\int_{r_c}^{r_o} r(T-T_0)dr\right\}$$

(Eqn. 5b)

$$\sigma_z = \frac{E}{1-\mu}\left\{\frac{2}{r_o^2-r_i^2}\Omega - \alpha_2(T-T_0)\right\}$$

(Eqn. 5c)

In the above equations, μ is Poisson's ratio. It is easily shown that these results reduce to the corresponding ones in Timoshenko [7] for a uniform material when $\alpha 1=\alpha 2$.

It should be noted that the effective elastic modulus, E, used in the program is calculated as a weighted average of the cross-sectional areas and elastic modulus values for the inner and outer material:

$$E = \frac{E_1 A_1 + E_2 A_2}{A_1 + A_2}$$ (Eqn. 6)

Where the variables denoted by the subscript 1 are for the inner material and denoted by the subscript 2 for the outer material.

As a sidelight if $\alpha_1=\alpha_2$ and T = constant, all of the stresses are zero. However if $\alpha_1 \neq \alpha_2$, a uniform temperature produces stresses except at the single temperature $T=T_0$. Hence, the selection of a reference temperature (T_0) has an influence in the case of piping with 2 layers. The value of T_0 is somewhat arbitrary, but in the case of reactor components, is usually taken to be the room temperature of 70°F so that the pipe would be stress-free when the plant was shut down. In xLPR-TIFFANY, T_0 is user specified.

The values of α, E, μ, ρ and c_{sp} are somewhat temperature-dependent, whereas xLPR-TIFFANY takes them to be independent of temperature. It is suggested that values at some intermediate temperature (e.g., average of maximum and minimum temperature) that occurs during the transient being analyzed be input to the software. An additional question arises concerning the coefficient of thermal expansion, α. Two values are possible for a given temperature; the instantaneous value at the given temperature, or the average value between 70°F and the given temperature. α is a user input, but the instantaneous value at some intermediate temperature is suggested since it is generally conservative – especially for pipes composed of a single material.

2.4.4 Other Loadings and Related Computations

The influence of thermal transients on stresses other than the radial gradient stresses is included in the TIFFANY computations.

Global Stresses: Temperature-dependent global stresses, such as pipe system stresses due to restraint of thermal expansion, can change during a thermal transient due to a change in the average temperature through the wall. A tension stress and a bending stress are input to TIFFANY (σ_T and σ_B) along with the temperature at which these values are applicable (T_{sig}, usually the normal operating temperature). These are considered to be the nonpressure global stresses at the temperature T_{sig}. These stresses are zero at T_0 = 70°F, and vary linearly with the average temperature in the pipe wall. The average temperature is computed by TIFFANY.

TIFFANY does not include the stresses that are present during normal operation, but only deviations from these stresses. The time variation of the pressure is a TIFFANY input (the deviation from the normal operating pressure is specified as Δp) and the effects on stress are computed by TIFFANY.

The circumference of the pipe is broken down into a user-defined number of segments, and the global bending stress varies from segment to segment.

<u>Stratification and Mechanical Transients:</u> xLPR-TIFFANY can also be used to obtain stresses and tables of maximum and minimum values of changes in stress intensity factors for transient identified as “stratification” or “mechanical”.

In the case of stratification transients, the stresses at each angular location and stress intensity factors due to bending stress are multiplied by a factor that is a user input (***DispFactorIn***).

In case of mechanical transients, a maximum and minimum membrane and bending stress are input and used to generate tables of the changes in maximum and minimum stress intensity factors for the selected crack sizes and for the angular location of each segment.

2.4.5 Stress Intensity Factors

The stress intensity factors for semi-elliptical inner surface cracks subject to radial gradient thermal stresses and other transients (pressure, mechanical and stratification) are evaluated at the deepest and surface points of part-through-wall (PW) cracks and for through-wall (TW) cracks [1,2].

In the following discussion K_{max} and K_{min} refer to the maximum and minimum values of the stress intensity factor during the transient being analyzed, which as noted in the previous subsection for stresses are excursions from the stress intensity factor during normal operation.

The values of K_{max} and K_{min} can be evaluated for either circumferential or axial cracks by use of the appropriate stress and influence functions. The axial stress is used in the evaluation of the stress intensity factors for circumferential cracks and the hoop stress is used for the axial cracks.

Values of *stress intensity factor* are evaluated for any crack size and for any time at which the stresses are evaluated during the transient. The actual time-variation of *stress intensity factor* for a given crack size is usually not of interest, with values of K_{max} and K_{min} being of more use. These values are needed for fatigue crack growth analyses that involve the transient change in cyclic stress intensity factors, ΔK (K_{max} - K_{min}). The times at which K_{max} occurs is not the same for all crack sizes. Values of K_{max}, and K_{min} are easily obtained from the temporal variation of *stress intensity factor*. The maximum and minimum stress intensity factors due to the radial gradient thermal stresses and other loading are output for a user-specified list of crack sizes, and angular locations in the case of circumferential cracks.

2.4.6 Sorting

The values of stress intensity factors as functions of time during the transient are available from intermediate TIFFANY calculations for the user-specified list of crack sizes, and angular locations in the case of circumferential cracks. These results are then sorted to obtain the maximum and minimum values for each crack size, with the results printed to files of K_{max} and K_{min} for the specified range of crack sizes.

2.4.7 Uncertainty Quantification

TIFFANY performs strictly deterministic computations. Uncertainties are present only in inputs to TIFFANY. Uncertainties in material properties are considered to be minimal, being available from the ASME Boiler and Pressure Vessel Code [9]. Uncertainties in time variation of the temperature do exist, but are not treated in TIFFANY. They are handled by the xLPR Framework using a procedure proposed in an appendix of the TIFFANY Model Validation Report [10].

3. TIFFANY MODULE DEVELOPMENT

In this section the module design requirements, inputs, verification and validation activities are described.

3.1 Module requirements

The functional and performance requirements for TIFFANY are identified in the SRD [3] and summarized in Table 6 of that document, which is also included in Table 5 of the Software Design Description (SDD) [11]. Table 6 of the TIFFANY SRD is included here as Table 1. This table also includes a short description of each requirement and the associated acceptance criterion. Note that the acronym DLL in this table refers to the dynamic link library for TIFFANY.

Table 1. List of TIFFANY Module Requirements

Requirement	Short Description	Acceptance Criteria
RTIF-1	The subroutine shall be written in Fortran such that it can be compiled to a DLL	The subroutine should be written in Fortran.
RTIF-2	The subroutine must exhibit the software design attributes of maintainability and portability.	The subroutine should be readable and modular
RTIF-3	The subroutine shall be implemented in terms of SI units, with unit conversion accomplished according to IEEE/ASTM SI 10 2010.	The subroutine inputs and outputs should be in SI units, with any necessary unit conversion accomplished according to the referenced standard.
RTIF-4	If the module is called from the DLL wrapper, communication of inputs and outputs shall be conducted with explicit passing of variables.	Static verification of framework SDD and wrapper DLL source code, if applicable.
RTIF-5	The subroutine must follow the best practices defined in [8]	The subroutine should follow the referenced best practices, where possible.
RTIF-6	The TIFFANY pre-processor shall call the Tiffany subroutine with a set of inputs that are in conformance with the required units, range of validity and data types, specified in Table 1	Static verification of framework SDD and wrapper DLL source code, if applicable.
RTIF-7	The TIFFANY pre-processor shall also accept the outputs in conformance with the required units, range of validity and data types, specified in Table 2	Static verification of framework SDD and wrapper DLL source code, if applicable.
RTIF-8	Upon receiving an error message from this module, the framework shall terminate the analysis (individual realization or complete simulation, at the discretion of the Computational Group)	Static verification of framework SDD and wrapper DLL source code, if applicable.

Requirement	Short Description	Acceptance Criteria
RTIF-9	Calculate T(r, t) with TIFFANY subroutine	Numerical procedure to independently check computations of temperature fields.
RTIF-10	Calculate σ(r, t) with TIFFANY subroutine	Numerical procedure to independently check computations of stress fields.
RTIF-11	Calculate maximum K at the deepest point for circumferential PW cracks, for each combination of a/h, a/c and the angular location around the circumference and return as a 3-d array (a/c, a/h, θ)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-12	Calculate minimum K at the deepest point for circumferential PW cracks, for each combination of a/h, a/c and the angular location around the circumference and return as a 3-d array (a/c, a/h, θ)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-13	Calculate maximum K at the surface point for circumferential PW cracks, for each combination of a/h, a/c and the angular location around the circumference and return as a 3-d array (a/c, a/h, θ)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-14	Calculate minimum K at the surface point for circumferential PW cracks, for each combination of a/h, a/c and the angular location around the circumference and return as a 3-d array (a/c, a/h, θ)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-15	Calculate maximum K for circumferential TW cracks due to membrane stress, for each combination of c and the angular location around the circumference and return as a 2-d array (c, θ)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-16	Calculate minimum K for circumferential TW cracks due to membrane stress, for each combination of c and the angular location around the circumference and return as a 2-d array (c, θ)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-17	Calculate maximum K for circumferential TW cracks due to bending stress, for each combination of c and the angular location around the circumference and return as a 2-d array (c, θ)	Numerical procedure to independently check the determination of maximum and minimum K values.

Requirement	Short Description	Acceptance Criteria
RTIF-18	Calculate minimum K for circumferential TW cracks due to bending stress, for each combination of c and the angular location around the circumference and return as a 2-d array (c, θ)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-19	Calculate maximum K at the deepest point for axial PW cracks, for each combination of a/h and a/c and return as a 2-d array (a/c, a/h)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-20	Calculate minimum K at the deepest point for axial PW cracks, for each combination of a/h and a/c and return as a 2-d array (a/c, a/h)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-21	Calculate maximum K at the surface point for axial PW cracks, for each combination of a/h and a/c and return as a 2-d array (a/c, a/h)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-22	Calculate minimum K at the surface point for axial PW cracks, for each combination of a/h and a/c and return as a 2-d array (a/c, a/h)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-23	Calculate maximum K for axial TW cracks due to pressure stress, for each crack size and return as a 1-d array (c)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-24	Calculate minimum K for axial TW cracks due to pressure stress, for each crack size and return as a 1-d array (c)	Numerical procedure to independently check the determination of maximum and minimum K values.
RTIF-25	Calculate maximum change in axial stress due to pressure during the transient	Independent numerical procedures or by examining the intermediate output
RTIF-26	Calculate maximum change in hoop stress due to pressure during the transient	Independent numerical procedures or by examining the intermediate output
RTIF-27	Calculate the maximum change of total axial stress at the ID (includes radial gradient thermal stresses pressure, membrane and bending) for each segment and return as a 1-d array	Independent numerical procedures or by examining the intermediate output
RTIF-28	Calculate the minimum change of total axial stress at the ID (includes RGTS, pressure, membrane and bending) for each segment and return as a 1-d array (θ)	Independent numerical procedures or by examining the intermediate output
RTIF-29	Calculate the time during the transient at which the maximum change of total axial stress at the ID occurs for each segment and return as 1-d array (θ)	Independent numerical procedures or by examining the intermediate output

Requirement	Short Description	Acceptance Criteria
RTIF-30	Calculate the time during the transient at which the minimum change of total axial stress at the ID occurs for each segment and return as 1-d array (θ)	Independent numerical procedures or by examining the intermediate output
RTIF-31	Calculate the maximum change of total hoop stress at the ID (includes RGTS and pressure)	Independent numerical procedures or by examining the intermediate output
RTIF-32	Calculate the minimum change of total hoop stress at the ID (includes RGTS and pressure)	Independent numerical procedures or by examining the intermediate output
RTIF-33	Calculate the time during the transient at which the maximum change of total hoop stress at the ID occurs	Independent numerical procedures or by examining the intermediate output
RTIF-34	Calculate the time during the transient at which the minimum change of total hoop stress at the ID occurs	Independent numerical procedures or by examining the intermediate output
RTIF-35	Calculate the rise time for axial stress at the ID for each segment and return as 1-d array (θ)	Independent numerical procedures or by examining the intermediate output
RTIF-36	Calculate the rise time for hoop stress at the ID	Independent numerical procedures or by examining the intermediate output
RTIF-37	Calculate the maximum temperature at the ID during the transient	Independent numerical procedures or by examining the intermediate output
RTIF-38	Calculate the minimum temperature at the ID during the transient	Independent numerical procedures or by examining the intermediate output

TIFFANY has no requirements for linking to other xLPR modules. The Stress intensity values are calculated using the stress intensity factor module embedded in TIFFANY which is identical to that used within the xLPR Framework. The output files from TIFFANY must be properly handled by xLPR, as discussed in Section 3.3.

3.2 Module Limitations

The TIFFANY module is capable of analyzing only one transient at a time. The module picks out only the largest and smallest values of the change in stress intensity factors for a given crack size and type. This means that intermediate maxima and minima are not captured. It is the responsibility of the user to properly define the transients being analyzed.

3.3 Integration Requirements

The TIFFANY module communicates through the DLL wrapper with the TIFFANY pre-processor which effectively provides a link to the xLPR computational framework. If the TIFFANY module is called from the DLL wrapper, communication of inputs and outputs shall be conducted with explicit passing of variables **[RTIF-4]**. This requirement is intended to provide local control of all module variables.

To invoke the TIFFANY module, the input pre-processor shall call the TIFFANY DLL with a set of inputs that are in conformance with the required units, range of validity and data types, specified in Table 2 below **[RTIF-6]**. The framework shall also accept the outputs in conformance with the required units, range of validity and data types, specified in Table 3 below **[RTIF-7]**.

The TIFFANY pre-processor should consult the Error Flag output to ensure the call to the TIFFANY module completed in a satisfactory manner. Table 5 of the TIFFANY SRD [3] describes each error condition and provides guidance for appropriate range of validity for each parameter.

3.4 Description of Inputs and Outputs

Tables 2 and 3, which are from the TIFFANY SRD [3], summarize the inputs and outputs for TIFFANY.

Table 2. Inputs to Subroutine TIFFANY

Variable	Data Type	Description
TitleIn	Character	Analysis description (1≤characters≤60)
IATypeIn	Integer	Transient type 1 – Thermal Transient 2 – Stratification Transient 3 – Mechanical Transient
IUnitsIn	Integer	1-US Customary 2-SI
IPrintIn	Integer	Print interval for intermediate output(Enter zero for no output)
PipeODIn	Real (8)	Pipe Outside Diameter
ThickIIn	Real (8)	Inside Material Thickness
ThickOIn	Real (8)	Outside Material Thickness
FlowXIn	Real (8)	Flow Rate
NuIn	Real (8)	Poisson's Ratio
NHist	Integer	No. of data in the time-temperature-pressure history (<=10000)
TimeA [ ]	Real (8)	NHist values of Time
FlTempA [ ]	Real (8)	NHist values of Fluid temperature
PrA [ ]	Real (8)	NHist values of Change in Pressure
TimeStepIn	Real (8)	Time step for computing temperatures, stresses and stress intensity factors
TzeroIn	Real (8)	Temperature at which clad/overlay stresses are zero
Youngs1In	Real (8)	Elastic Modulus for inner material 1
Rho1In	Real (8)	Density
Cp1In	Real (8)	Specific Heat
Alpha1In	Real (8)	Thermal Expansion Coeff.
K1T1In	Real (8)	Thermal Conductivity at Temperature T11
K1T2In	Real (8)	Thermal Conductivity at Temperature T12
T11In	Real (8)	Temperature T11
T12In	Real (8)	Temperature T12
Youngs2In	Real (8)	Elastic Modulus for outer material 2
Rho2In	Real (8)	Density
Cp2In	Real (8)	Specific Heat
Alpha2In	Real (8)	Thermal Expansion Coeff.
K2T1In	Real (8)	Thermal Conductivity at Temperature T21
K2T2In	Real (8)	Thermal Conductivity at Temperature T22
T21In	Real (8)	Temperature T21

Variable	Data Type	Description
T22In	Real (8)	Temperature T22
SigMNOIn	Real (8)	Normal thermal expansion membrane stress
SigBNOIn	Real (8)	Normal thermal expansion bending stress
OpTempIn	Real (8)	Operating Temperature (corresponding to SigMNO, SigBNO)
SigMminIn	Real (8)	Minimum membrane stress (only for IYType = 2 or 3)
SigMmaxIn	Real (8)	Maximum membrane stress (only for IYType = 2 or 3)
SigBminIn	Real (8)	Minimum bending stress (only for IYType = 2 or 3)
SigBmaxIn	Real (8)	Maximum bending stress (only for IYType = 2 or 3)
DispFactorIn	Real (8)	Displacement control factor (only for IAType=2)
NumSegsIn	Integer	No. of Crack Initiation Segments (<=100)
NAOCIn	Integer	No. of a/c values for the evaluation of K for PW cracks (<=100)
NAOTIn	Integer	No. of a/h values for the evaluation of K for PW cracks (<=100)
NCTWCircIn	Integer	No. of c values for the evaluation of K for TW Circ. cracks (<=100)
NCTWAxIn	Integer	No. of c values for the evaluation of K for TW Axial cracks (<=100) (only for IAType=1)
AOCa [ ]	Real (8)	NAOC a/c values
AOTa [ ]	Real (8)	NAOT a/h values
CTWCirca [ ]	Real (8)	NCTWCirc c values
CTWAxa [ ]	Real (8)	NCTWAx c values

Detailed description of the inputs needed by **TIFFANY** is given in this section. Note on the data types:

Integer – A whole number without a decimal point

Real (8) – A floating point number

Character – Any alpha-numeric characters except @#$%^&*()

[] – Indicates an array input

Table 3. Outputs from Subroutine TIFFANY

Variable	Description	Notes
Circumferential Cracks		
KCircDeepMxO[ ]	3-d array [a/t, a/c, Segment Number] of **maximum** K for the **deepest** point	PW Cracks
KCircDeepMnO[ ]	3-d array [a/t, a/c, Segment Number] of **minimum** K for the **deepest** point	
KCircSurfMxO[ ]	3-d array [a/t, a/c, Segment Number] of **maximum** K for the **surface** point	
KCircSurfMnO[ ]	3-d array [a/t, a/c, Segment Number] of **minimum** K for the **surface** point	
KCircTWMxMO[ ]	2-d array [c, Segment Number] of **maximum** K	TW Cracks
KCircTWMnMO[ ]	2-d array [c, Segment Number] of **minimum** K	
KCircTWMxBO[ ]	2-d array[c, Segment Number] of **maximum** K	TW Cracks
KCircTWMnBO[ ]	2-d array [c, Segment Number] of **minimum** K	
PaxStrMaxO	Maximum pressure stress change (axial)	Max. change for input PrA [ ]
AllAxStrMaxO[ ]	1-d array [Segment Number] of Maximum axial ID stress (included RGTS, Pr, membrane, bending)	Used for fatigue initiation
AllAxStrMinO[ ]	1-d array [Segment Number] of Minimum axial ID stress (included RGTS, Pr, membrane, bending)	Used for fatigue initiation
TimeMaxAllAxialO[ ]	1-d array [Segment Number] of Time at which the maximum ID stress occurs	
TimeMinAllAxialO[ ]	1-d array [Segment Number] of Time at which the minimum ID stress occurs	
RiseTimeAxStrO[ ]	1-d array [Segment Number] of Rise time for axial stress at the ID	
Axial Cracks		
KAxDeepMxO[ ]	Two-d array [a/t, a/c] of **maximum** K for the **deepest** point	PW Cracks
KAxDeepMnO[ ]	Two-d array [a/t, a/c] of **minimum** K for the **deepest** point	
KAxSurfMxO[ ]	Two-d array [a/t, a/c] of **maximum** K for the **surface** point	
KAxSurfMnO[ ]	Two-d array [a/t, a/c] of **minimum** K for the **surface** point	
KAxTWMxO[ ]	One-d array [c] of **maximum** K	TW Cracks
KAxTWMnO[ ]	One-d array [c] of **minimum** K	

PhoopStrMaxO	Maximum pressure stress change (hoop)	Max. change for input PrA [ ]
AllHoopStrMaxO	Maximum hoop ID stress (included RGTS, Pr, membrane, bending)	Used for fatigue initiation
AllHoopStrMinO	Minimum hoop ID stress (included RGTS, Pr, membrane, bending)	Used for fatigue initiation
TimeMaxAllHoopO	Time at which the maximum ID hoop stress occurs	
TimeMinAllHoopO	Time at which the minimum ID hoop stress occurs	
RiseTimeHpStrO	Rise time for hoop stress at the ID	
TempMaxO	Maximum temperature at the ID	Only for Type 1 input
TempMinO	Minimum temperature at the ID	
Ierror	Integer, Error Flag	Value between 101-120,123-128,131-144 or 0

Note: K in this table is the excursion from normal operation.

The material properties that need to be input to TIFFANY are summarized in Table 4

Table 4. Material Properties Required for TIFFANY

Name	Sym.	Units
thermal conductivity	K	W/(m-°K)
specific heat	C	J/(kg-°K)
Density	ρ	kg/m^3
thermal diffusivity	κ	m^2/s
Young's modulus	E	MPa
Poisson's ratio	ν	--
coeff of thermal exp	α	°C^{-1}

Values of these properties for common piping materials are available in the TIFFANY STP [12].

A key input to TIFFANY is the time/temperature/pressure history of the transient. This can come from a variety of sources, such as design reports or actual plant measurements. This input itself is one of the major causes of uncertainty in the TIFFANY output. However, the transient input from design reports is typically very conservative and would be expected to bound the transient input from actual plant measurements.

3.5 Module Verification and Validation

The verification of the proper functionality of the TIFFANY module is detailed in the Software Test Plan (STP) [12]. The test plans define a set of test cases that are sufficient to determine whether the module encompasses all of the functional requirements enumerated in the

TIFFANY SRD [3]. The tests for the computation of temperatures are based on closed form solutions for transient temperature fields. Comparisons of TIFFANY temperature and stress results with closed form solutions are provided in the TIFFANY test results report (STRR) [4]. Additionally, TIFFANY stress and temperature results are compared with finite element calculations in the TIFFANY models validation report (MVR) [10].

The scope of the testing includes only the functionality of TIFFANY. The scope does not include the wrapper code that is used to interface the module with the GoldSim Framework. Tests on the interfacing of the pre-processor output with the Framework are expected to be performed during integration testing defined in a separate framework test plan.

3.6 Flow Diagram

A summary of the basic process structure of TIFFANY is shown in Figure 3. The constituent actions in the activity diagram are described in further detail in the TIFFANY SDD [11].

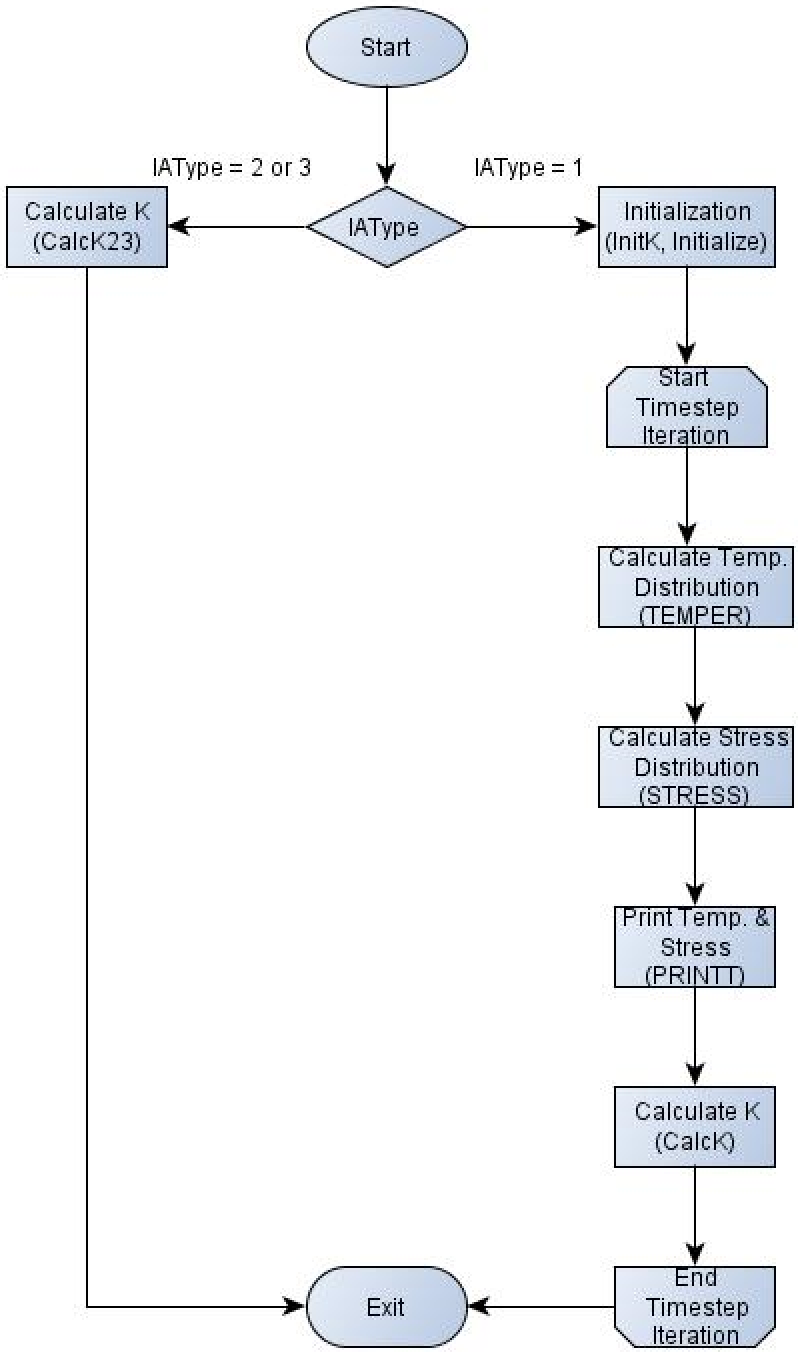

Figure 3. TIFFANY Logic Control Flow

4. RECOMMENDATIONS FOR XLPR VERSION 3 MODIFICATIONS

No recommendatioins for xLPR Version 3 modifications of TIFFANY are made at this time. Lessons learned during the interfacing of TIFFANY output with the Goldsim framework and exercising the TIFFANY capability in xLPR runs will probably point to some desireable modifications in the future.

5. LESSONS-LEARNED

None at this time.

6. SUMMARY

This model report describes the overall development of the TIFFANY module for xLPR version 2. The software requirements and design description are defined in [3,11] and a prescribed test plan in [12]. The test plan includes comparisons with closed form temperature and stress solutions, as well as finite element computations [10]. The testing itself is documented in the TIFFANY STRR [4]. A review of inputs and outputs is provided. TIFFANY itself is deterministic, but there are uncertainties in the inputs – primarily the time/temperature/pressure history of the transient.

7. REFERENCES

[1] xLPR-SRD-KPW: xLPR Software Requirements Specification for K Calculator for Circumferential and Axial Part-Through-Wall Cracks, Version 2.2.

[2] xLPR-SRD-KTW: xLPR Software Requirements Specification for K Calculator for Circumferential and Axial Through-Wall Cracks, Version 2.2.

[3] xLPR-SRD-TIFF: *xLPR Software Requirements Description for the TIFFANY Module*, Version 1.0.

[4] xLPR-STRR-TIFF: *xLPR Software Test Results Report for the TIFFANY Module*, Version 1.0.

[5] D.D. Dedhia, D.O. Harris, and V.E. Denny*, "TIFFANY: A Computer Code for Thermal Stress Intensity Factors for Surface Cracks in Clad Piping,"* Science Applications, Inc. Report SAI–331–82–PA, Palo Alto, California, November 1982 (LLNL Contract No. 8679501, Task 2).

[6] J.F. Harvey, *Theory and Design of Pressure Vessels*, van Nostrand and Reinhold, New York, second edition, 1991

[7] D.K. Edwards, V.E. Denny and A.F. Mills*, Transfer Processes,* McGraw-Hill Book Company, 2nd Edition, New York 1978

[8] S. Timoshenko and J.N. Goodier*, Theory of Elasticity, Second Edition,* McGraw Hill Book Co., New York, 1951

[9] ASME Boiler and Pressure Vessel Code, Section II, Part D, *Properties*

[10] xLPR-MVR-TIFF: xLPR Module Validation Report for TIFFANY, Version 1.0.

[11] xLPR-SDD-TIFF: *xLPR Software Design Description for the TIFFANY Module*, Version 1.0.

[12] xLPR-STP-TIFF: *xLPR Software Test Plan for the TIFFANY Module*, Version 1.0.