The SAS4A/SASSYS-1 Safety Analysis Code System

Nuclear Engineering Division
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The SAS4A/SASSYS-1 Safety Analysis Code System

Chapter 13:
Cladding Motion Model — CLAP

Nuclear Engineering Division
Argonne National Laboratory

March 31, 2017
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<td>Moving cladding cross-sectional area</td>
<td>m$^2$</td>
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<td>AFRV</td>
<td>Input constant in single-phase friction factor formula, Eq. 13.2-5</td>
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<td>$A_f$</td>
<td>Total area allowed for cladding by the fuel</td>
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<td>$r_{NR,NT}$</td>
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<td>Half-thickness of molten cladding layer</td>
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<td>Half-thickness of the refrozen cladding</td>
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<td>Symbol</td>
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<td>Fuel surface temperature</td>
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<td>T_i</td>
<td>Intact cladding temperature</td>
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<td>Reference temperature in density Eq. 13.2-38</td>
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<td>Refrozen cladding temperature</td>
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<td>T_w</td>
<td>Structure temperature</td>
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<td>t</td>
<td>Time</td>
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<td>Time at beginning of current heat-transfer time step</td>
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<td>W_j</td>
<td>Cladding reactivity worth distribution</td>
<td>(\partial k/k)-kg</td>
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<td>Vapor mass flowrate</td>
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<td>(\theta)</td>
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<td>Cladding viscosity at the liquidus temperature</td>
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<td>Solid cladding pseudo-viscosity, Eq. 13.2-18c</td>
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<td>Cladding viscosity at the solidus temperature</td>
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<td>(\mu_v)</td>
<td>Vapor viscosity</td>
<td>Pa·s</td>
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<td>(\xi_1, \xi_2, \xi_3)</td>
<td>Computed coefficients</td>
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<td>Molten cladding density</td>
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<td>Density of cladding at the liquidus temperature</td>
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<td>(\bar{\psi})</td>
<td>Mean ratio of thermal-to-momentum eddy diffusivities</td>
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13.1 Introduction and Overview

13.1.1 Background and Description of the CLAP Physical Model

The CLAP Model [13-1, 13-2] computes cladding relocation and phase changes for accident situations in which the fuel geometry is still essentially intact. Such a situation typically arises in undercooling accidents during which coolant voiding and pin dryout occur, followed by rapid heating and subsequent melting of the cladding. In the usual accident scenario, the cladding motion proceeds as follows: (i) the molten cladding may initially rise due to the pressure gradient and viscous shear forces generated by the sodium coolant vapor flow in the dried-out section of the core, (ii) the rising molten cladding then freezes upon encountering cooler structure in the region immediately above the active fuel (either the upper reflector or upper blanket region, depending upon the reactor design), and (iii) the upper frozen-cladding blockage throttles the vapor flow, thus allowing the remaining molten cladding to drain under the influence of gravity. The cladding motion and phase changes significantly affect the subsequent course of events in the scenario both through the influences of cladding-motion-related reactivity changes and frozen-cladding blockages that possibly inhibit later fuel motions.

The available SAS3D cladding relocation model, CLAZAS [13-3], is inflexible in calculation of the consequences for such diverse mechanistic and/or postulated phenomena. This model suffers from several shortcomings in the estimation of cladding accelerations. First, the use of large cladding segments can lead to a significant change in results following relatively minor input changes. Second, the model-dependent Lagrangian mesh leads to difficulties in integrating consistently with the voiding dynamics and fuel motion models. Third, the formalism does not provide flexibility with respect to the mode of cladding refreezing or with respect to variations in the time-dependent coupling to the sodium-vapor dynamics. If treated correctly, the influence of sodium-vapor dynamics could result in a possible display of oscillatory effects.

The CLAP model uses and Eulerian numerical formulation coupling the time-dependent continuity, momentum, and energy equations for a film of moving cladding, the continuity and energy for sodium vapor, and the SAS4A pin heat-transfer calculation. This is accomplished by interconnecting an implicit solution for the low-density sodium vapor with an explicit, modified upwind differencing procedure for the high-density cladding. Axial resolution depends on the mesh spacing selected by the user. The key phenomena influencing cladding motion in CLAP are the degree of interfacial sodium vapor friction and the cladding heat transfer. Input that controls these phenomena permits a variety of experimental situations to be simulated.

As shown in the schematic in Fig. 13.1-1, the CLAP model divides the core axially into two types of zones. In the central zone, the cladding is molten and is in motion. In that region, heat is transferred directly from the fuel surface to the molten cladding. In the zones at either end of the fueled region is intact cladding. Due to cladding motion, the intact cladding may be coated with refrozen cladding and/or molten cladding.
13.1.2 CLAP Module Structure and Interaction with Other SAS4A Models

The initiation of CLAP and the decision for adding axial segments to the molten-cladding zone occurs in the fuel-pin model TSHTRV. During cladding motion, the fuel-pin model TSHTRV continues to evaluate the fuel temperatures and, outside of the molten zone, the temperatures of the intact cladding. Coupling between TSHTRV and CLAP allows for heat transfer between the fuel and molten cladding in the molten-cladding zone and between the initial cladding and refrozen (or molten) cladding outside the molten zone.

The CLAP subroutines are called every coolant time step and, as shown in Fig. 13.1-2, are called from various locations in the sodium voiding module. The functions of the CLAP subroutines are as follows:

- **TSCLD1** - (i) initiates CLAP variables, (ii) adds segments to molten zone, (iii) calculates local heat transfer between molten steel and fuel within the molten zone, (iv) calculates local heat transfer between the initial cladding, refrozen cladding (if any), and molten cladding (if any) outside of the molten zone, and (v) computes mass and areas of the refrozen and molten cladding allowing for convection and phase change;

- **TSCLD2** - solves the momentum equation to obtain the velocity of the molten cladding film and contains the CLAP output and debug print statements;

- **SODFRC** - computes the two-phase friction factor used to evaluate the interfacial shear stress between the sodium vapor and molten steel;

- **DENSIT** - evaluates the cladding melt fraction, temperature, and density as a function of cladding specific internal energy.

The CLAP subroutine TSCLD1 computes the current (local) vapor flow areas and hydraulic diameters, which are used by the sodium voiding model. Also, TSCLD1 may reduce the current coolant time step, if necessary (based on a Courant condition criterion), and require the coolant dynamics model to reevaluate current flow parameters.

The CLAP subroutine TSCLD2 is called later and utilizes updated sodium vapor velocities and pressures to compute the molten cladding velocity for the beginning of the next time step. Local two-phase friction factors (to evaluate the gas/liquid interfacial stress), which are computed by TSCLD2 for the next time step, are passed to the sodium voiding model.

Coupling of CLAP with the reactivity model consists of current cladding mass distributions (axial) computed in TSCLD1 being utilized in the subroutine FEEDBK to evaluate the reactivity change due to cladding relocation.
Fig. 13.1-1. Schematic of CLAP Geometry Treating Cladding Relocation
Fig. 13.1-2. CLAP Flowchart
13.2 Mathematical Model

13.2.1 Sodium Vapor Flow Model

The sodium vapor flow generates the axial pressure gradients and interfacial shear forces, which influence the motion of molten cladding. The cladding motion in turn changes flow areas, hydraulic diameters, and surface roughness which all affect the sodium vapor flow. The governing equations for the sodium vapor, while presented elsewhere (Section 12.6.1) in more detail, are reproduced here to show the intimate coupling between the sodium vapor dynamics and cladding motion. The conservation equations for the sodium vapor are

\[
\frac{\partial}{\partial t} \left(A_v \rho_v \right) + \frac{\partial w}{\partial z} = \dot{m}_v \tag{13.2-1}
\]

\[
\frac{\partial w}{\partial t} + \frac{\partial}{\partial z} \left( \frac{w^2}{A_v \rho_v} \right) + A_v \left[ \frac{\partial p}{\partial z} + F_v \right] = \begin{cases} 
\dot{m}_v \frac{w}{A_v \rho_v}, & \text{if condensing} \\
0, & \text{if vaporizing} \end{cases} \tag{13.2-2a}
\]

where

\[ A_v = \text{vapor flow area} \]
\[ \rho_v = \text{vapor density} \]
\[ w = \text{vapor mass flowrate} \]
\[ \dot{m}_v = \text{the rate of vapor generation per unit length of channel} \]
\[ \frac{\partial p}{\partial z} = \text{channel axial pressure gradient} \]
\[ F_v = \text{cladding/vapor interfacial friction force per unit volume of vapor.} \]

The friction force term is evaluated from the following equation:

\[
F_v = \frac{f_{sf} M w \left|w\right|}{2 \rho_v A_v^2 D_v} \tag{13.2-3}
\]

where

\[ f_{sf} = \text{single-phase friction factor} \]
\[ M = \text{flooding multiplier} \]
\[ D_v = \text{hydraulic diameter for the vapor.} \]
The hydraulic diameter is estimated by

\[ D_v = D_h \sqrt{\alpha} \]  

(13.2-4)

where

\( D_h \) = hydraulic diameter for bare fuel or fuel pin (depending upon the zone)

\( \alpha \) = vapor fraction based on area available for molten steel plus vapor.

This equation assumes that the hydraulic diameter \( D_v \) varies as the square root of the area \( \nu \) (which would be exact for a circular vapor flow passage) and hence scales as the square root of vapor fraction (proportional to the flow area).

The smooth wall (single-phase) friction factor is given by

\[ f_{sf} = AFRV \left( \frac{Re}{BFRV} \right) \]  

(13.2-5)

\[ (Re) = \frac{wD_v}{A_v \mu_v} \]  

(13.2-6)

where

AFRV, BFRV = input constants

\( \mu_v \) = vapor viscosity.

For consistency, the inputed constants AFRV and BFRV used in CLAP are identical to those used in the sodium voiding model.

The flooding multiplier is flow-regime dependent. The transition from smooth wall friction (\( M = 1 \)) to a chaotic two-phase flow structure (\( M = M_{2\Phi} \), where \( M_{2\Phi} \) is defined later) occurs nominally when the vapor velocity exceeds the flooding velocity. The current version of CLAP uses the correlation of Fauske, et al. [13-4]:

\[ v_{flood} = \left[ \frac{32 \rho_c g \Delta r_c}{3 \rho_v f_{sf} M_{2\Phi}} \right]^{1/2} \]  

(13.2-7)

where

\( \Delta r_c \) = one-half the molten cladding thickness

\( \rho_c \) = molten cladding density.

The CLAP model has a hysteresis effect in the treatment of the flooding multiplier whereby flooding and the inverse, deflooding, occur at slightly different velocities as follows:
set \( M^n = M_{2\phi} \), if \( M^{n-1} = 1 \) and \( |w/ A, \rho| > 1.1v_{\text{flood}} \) (13.2-8)

set \( M^n = 1 \), if \( M^{n-1} = M_{2\phi} \) and \( |w/ A, \rho| < 0.9v_{\text{flood}} \) (13.2-9)

where \( n \) is the current time-step number. If the conditions in either Eq. 13.2-8 or 13.2-9 are not met, then the previous value of \( M \) is retained.

The two-phase friction multiplier is given by

\[
M_{2\phi} = I \cdot \left[ 1 + \epsilon (1 - \alpha) \right] \quad \text{for } \alpha > \alpha_{\text{crit}}
\]

(13.2-10a)

\[
M_{2\phi} = I \cdot \left[ 1 + \epsilon (1 - \alpha_{\text{crit}}) \right] \quad \text{for } \alpha \leq \alpha_{\text{crit}}
\]

(13.2-10b)

where \( \epsilon \) and \( \alpha_{\text{crit}} \) are input and \( I \) is an incoherence multiplier. For values of \( \epsilon = 75 \) and \( \alpha_{\text{crit}} = 0 \), Eq. 13.2-10 is equivalent to the Wallis correlation [13-5].

Radial incoherency in cladding melting, which occurs during the early portion of cladding motion, results in a lower bundle pressure drop and lower cladding velocity than predicted by one-dimensional models that ignore this effect [13-6]. The incoherence multiplier allows for this incoherency effect by temporarily reducing the two-phase friction multiplier during early cladding motion in the following manner:

\[
I = \left[ \frac{fps}{(fps)_0} \right]^x \quad \text{for } fps < (fps)_0 \]

(13.2-11a)

\[
I = 1 \quad \text{for } fps \geq (fps)_0 \]

(13.2-11b)

where \( fps \) are full-power seconds since cladding first moved in a channel and \( (fps)_0 \) and \( x \) are input constants.

The code sets \( M_{2\phi} \) equal to unity, equivalent to a smooth wall friction factor, if the value of \( M_{2\phi} \) computed by Eq. 13.2-10 is less than unity. Consequently, the effect of the multiplier "\( I \)" is to delay flooding by \( (fps)_0 \) full-power seconds. For cases where the vapor velocity is below that necessary for flooding, neither \( (fps)_0 \) nor \( \epsilon \) will have any effect on the cladding motion. Values for \( (fps)_0 \) and \( x \) of 0.3 and 3 are provisionally recommended; better values will be determined later by calibration of the CLAP model using experimental data.

### 13.2.2 Moving Cladding Basic Equations

The mass, momentum, and energy conservation equations for moving (molten) cladding are
\[
\frac{\partial}{\partial t}(\rho_c A_c) + \frac{\partial}{\partial z}(\rho_c A_c v_c) = \dot{m}_c
\]  
(13.2-12)

\[
\frac{\partial}{\partial t}(\rho_c A_c e_c) + \frac{\partial}{\partial z}(\rho_c A_c v_c^2) + A_e \frac{\partial p}{\partial z} + A_e F_p - A_e F_v + A_e \rho_c g = \begin{cases} 
\dot{m}_c v_c \text{ if freezing} \\
0, \text{ if melting}
\end{cases}
\]  
(13.2-13a)

\[
\frac{\partial}{\partial t}(\rho_c A_c e_c) + \frac{\partial}{\partial z}(\rho_c A_c v_c e_c) = \phi_c P_r + \dot{m}_c e_c
\]  
(13.2-14)

\(A_c\) = moving cladding cross-sectional area

\(v_c\) = moving cladding velocity

\(\dot{m}_c\) = mass rate of melting of substrate per unit length of channel (or rate of freezing if negative)

\(F_p\) = pin friction-force per unit volume of molten cladding

\(e_c\) = moving cladding internal energy

\(\phi_c\) = flux of sensible heat from the solid/liquid interface into the molten cladding

\(P_r\) = perimeter of solid/liquid interface.

The pin or bare-fuel friction force is evaluated by the following:

\[
F_p = c_f \rho_c v_c |v_c| / 2D_c
\]  
(13.2-15)

where

\(c_f\) = pin friction factor

\(D_c\) = molten cladding hydraulic diameter.

The CLAZAS [13-3] formulation for the friction factor has been incorporated into CLAP:

\[
c_f = \frac{64}{Re} \text{ for } Re < (Re)_{\text{break}}
\]  
(13.2-16a)
Cladding Motion Model — CLAP

\[ c_f = b_f \text{ for } \text{Re} \geq (\text{Re})_{\text{break}} \] (13.2-16b)

where \( \text{Re} \) is the molten-cladding Reynolds number defined by:

\[ \text{Re} = \frac{D_c \rho_c |v_c|}{\mu_c} \] (13.2-17)

\((\text{Re})_{\text{break}}\) is the critical Reynolds number for the transition from laminar to turbulent friction and \( b_f \) is the turbulent Moody friction factor. The CLAZAS derived values for \( (\text{Re})_{\text{break}} \) and \( b_f \) of \( 2.1 \times 10^3 \) and \( 2.0 \times 10^{-2} \) are currently recommended as input values.

The cladding viscosity depends upon the cladding temperature \( T_c \) and melt-fraction \( f \) as follows

\[ \mu_c = \mu_m \exp\left( a / T_c - a / T_m \right) \text{ for } T_c > T_m \] (13.2-18a)

\[ \mu_c = (\mu_t - \mu_m) (1 - f)^q + \mu_m \text{ for } T_c = T_m \] (13.2-18b)

\[ \mu_c = \mu_s \text{ for } T_c < T_m \] (13.2-18c)

where \( T_m \) is the cladding melting temperature, \( \mu_m, \mu_t, \mu_s \) are the user-supplied viscosities for solid cladding, at the solidus temperature, and cladding at the liquidus temperature, and \( a \) and \( q \) are input constants. Values for \( \mu_m \) and \( a \) of \( 6.42 \times 10^{-3} \) Pa·s and \( 5492 \) K are recommended [13-7]. The input parameters \( \mu_t, \mu_s \) and \( q \) are not properties per se, but are constants in a phenomenological model and hence need to be determined by calibration with cladding motion test data. In general, the values selected for \( \mu_t \) and \( \mu_s \) should be sufficiently large to effectively arrest cladding motion for solid cladding. Provisional values for both \( \mu_t \) and \( \mu_s \) of \( 10^4 \) Pa·s (\( 10^5 \) poise), from the CLAZAS sample problem [13-3], and for \( q \) of 0.5 are recommended.

The momentum and energy Eqs. 13.2-13 and 13.2-14 are converted to non-conservative form using Eq. 13.2-12, giving the following:

\[ \rho_c \left[ \frac{\partial v_c}{\partial t} + v_c \frac{\partial v_c}{\partial t} \right] + \frac{\partial p}{\partial z} + F_p - \frac{A_v}{A_c} F_v + g \rho_c = \begin{cases} 0 & \text{if freezing} \\ -m_c \dot{v}_c / A_c & \text{if melting} \end{cases} \] (13.2-19a)

\[ \frac{\partial e_c}{\partial t} + v_c \frac{\partial e_c}{\partial z} = \frac{\phi_c P_c}{A_c \rho_c} \] (13.2-20)
13.2.3 Refrozen Cladding Basic Equations

The conservation equations for the refrozen steel layer are

\[
\frac{\partial}{\partial t} (\rho_s A_s) = -\dot{m}_c \tag{13.2-21}
\]

\[
\frac{\partial}{\partial t} (\rho_s A_s e_s) = \phi_r P_e - \phi P_r - \dot{m}_c e_s \tag{13.2-22}
\]

where

- \( \rho_s \) = refrozen steel density
- \( A_s \) = refrozen steel cross-sectional area
- \( e_s \) = refrozen steel internal energy
- \( \phi_r \) = heat flux at the interface between intact cladding and refrozen cladding
- \( P_e \) = outer perimeter of intact cladding
- \( \phi \) = flux of sensible heat from the refrozen cladding to the melt (solid/liquid) interface.

Recall that the quantity \( \dot{m}_c \) was the rate of melting (negative for freezing) and hence appears as a sink (negative sign) in the refrozen cladding Eqs. 13.2-21 and 13.2-22.

By manipulating the preceding equations, we obtain the nonconservative form of the energy equation:

\[
\frac{\partial e_s}{\partial t} = \frac{(\phi_r P_e - \phi P_r)}{\rho_s A_s} \tag{13.2-23}
\]

Note that the sensible heat fluxes on either side of the melt layer are not the same (see Fig. 13.2-1b). The difference \( \phi_{hf} \) is the heat flux for fusion, defined by

\[
\phi_{hf} = \phi - \phi_c \tag{13.2-24}
\]

The rate of melting (or freezing, if negative) is directly related to the fusion heat flux:

\[
\dot{m}_c = P_e \phi_{hf} / \lambda \tag{13.2-25}
\]

where \( \lambda \) is an effective heat of fusion of the cladding defined as
\[ \dot{\lambda} = e_c - e_s \]  

(13.2-26)

### 13.2.4 Heat-transfer Relationships

#### 13.2.4.1 Moving Cladding on Bare Fuel

The configuration in the molten zone is shown in Fig. 13.2-1a. There is no solid cladding in this region and, therefore, the heat flux for melting, \( \phi_{hf} \), is zero. The sensible heat flux is given by

\[ \phi_c = h (T_f - T_c) \]  

(13.2-27)

where

- \( T_f \) = fuel pellet surface temperature
- \( h \) = coefficient of heat transfer from the fuel to molten cladding.

The heat-transfer coefficient for the moving cladding is defined from a correlation for liquid-metal heat transport as

\[ \frac{hD_c}{k_c} = C_1 \left( D_c \rho_c c_{pc} \left| V_c \right| / k_c \right)^{C_2} + C_3 \]  

(13.2-28)

where

- \( k_c \) = molten cladding thermal conductivity
- \( c_{pc} \) = molten cladding specific heat capacity
- \( C_1, C_2, C_3 \) = input constants.
Fig. 13.2-1. Schematic Showing the Different Heat-Transfer Configuration in CLAP
The same correlation and constants are used for computing heat-transfer coefficients for single-phase sodium flow in the channel, (Eq. 3.3-9 of Chapter 3). The correlation of Maresca and Dwyer [13-8] for in-line flow in rod bundles is recommended, for which the constants are:

\[ C_1 = 0.0155 (\bar{\psi})^{0.86} \quad (13.2-29a) \]

\[ C_1 = 0.86 \quad (13.2-29b) \]

\[ C_3 = 6.66 + 3.126 (P/D) + 1.184 (P/D)^2 \quad (13.2-29c) \]

where \( \bar{\psi} \) = mean ratio of the thermal and momentum diffusivities, and \( P/D \) = rod pitch-to-diameter ratio. Since the code does not allow for flow-rate-dependent values for \( C_i \), it is suggested that \( \bar{\psi} \) be set equal to unity in Eq. 13.2-29a with the understanding that the resulting heat-transfer coefficients will be slightly overestimated.

### 13.2.4.2 Moving Cladding on Intact and Refrozen Cladding

Various configurations can exist in the region outside the molten zone, depending upon whether or not moving cladding and/or refrozen cladding are present in addition to the original intact solid cladding. In this subsection, we consider the case where all three components are present (see Fig. 13.2-1b). The various heat fluxes shown in the figure are given by

\[ \phi_r = k_c (T_i - T_s) / (\Delta r_i + \Delta r_s) \quad (13.2-30) \]

\[ \phi_r = k_c (T_s - T_m) / \Delta r_s \quad (13.2-31) \]

\[ \phi_c = h (T_m - T_c) \quad (13.2-32) \]

where

- \( T_i \) = temperature of the intact solid cladding
- \( T_s \) = temperature of the refrozen cladding
- \( T_m \) = cladding melting temperature
- \( \Delta r_i \) = half-thickness of the intact solid cladding
- \( \Delta r_s \) = half-thickness of the refrozen cladding.
The film coefficient formula is identical to Eq. 13.2-28 and the fusion heat flux $\phi_{nf}$ is given by Eq. 13.2-24.

13.2.4.3 Intact and Refrozen Cladding

In the absence of moving cladding (see Fig. 13.2-1c), we set $\phi = 0$ and $\phi_{nf} = 0$. The heat transfer between the initial and refrozen cladding is computed from

$$
\phi_r = k_c \frac{(T_i - T_s)\Delta r_i}{\Delta r_i + \Delta r_s}
$$

(13.2-33)

which is identical to Eq. 13.2-30.

13.2.4.4 Intact and Moving Cladding

The moving cladding may be sufficiently hot to melt through the layer of refrozen cladding; this results in the configuration (see Fig. 13.2-1d) in which just the intact cladding and moving cladding are present. In the numerical model this situation also arises when moving cladding first contacts the intact cladding in an axial segment, in which case refrozen cladding is formed and will be present in the next time step.

The heat fluxes $\phi_1$ and $\phi_2$ and trial heat flux are calculated as follows

$$
\phi_1 = k_c (T_i - T_m) \Delta r_i
$$

(13.2-34)

$$
\phi_2 = h(T_m - T_c)
$$

(13.2-35)

$$
\phi_{trial} = \phi_1 - \phi_2
$$

(13.2-36)

Recalling that $\phi_r$ is the outer surface heat flux for the initial cladding, $\phi_c$ the sensible heat flux for moving cladding, and $\phi_{nf}$ the latent heat flux associated with refrozen cladding, we have

$$
\phi_{nf} = 0, \phi_r = \phi_2, \text{ and } \phi_c = \phi_2 \quad \text{for } \phi_{trial} \geq 0
$$

(13.2-37a)

$$
\phi_{nf} = \phi_{trial}, \phi_r = \phi_1, \text{ and } \phi_c = \phi_2 \quad \text{for } \phi_{trial} < 0
$$

(13.2-37b)

13.2.5 Cladding Physical Properties Relationships

The density of the solid and liquid cladding are assumed to be linear functions of temperature:

$$
\rho_s = \rho_s^0 \left[ 1 - 3\beta(T - T_{ref}) \right]
$$

(13.2-38)
\[ \rho_c = \rho_c^0 \left[ 1 - C(T - T_m) \right] \] (13.2-39)

where

\[ \rho_s^0 = \text{density of solid cladding at reference temperature } T_{\text{ref}} \]

\[ \rho_c^0 = \text{density of cladding at the liquidus temperature} \]

\[ \beta = \text{linear coefficient of thermal expansion for solid} \]

\[ C = \text{volumetric coefficient of thermal expansion for liquid}. \]

For partly-molten cladding, the density is evaluated using

\[ \rho = \left[ (1 - f) / \rho_s(T_m) + f / \rho_c \right] \] (13.2-40)

where \( f \) is the melt fraction as defined by Eq. 13.2-43.

The internal energies of the solid and molten cladding are also assumed to be linear functions of temperature

\[ e_s = c_{ps} T \] (13.2-41)

\[ e_c = e_c^o + c_{pc} T \] (13.2-42)

where \( e_c^o = \lambda^o + (C_{ps} - C_{pc}) T_m \), and \( \lambda^o = \text{heat of fusion} \). For mixtures, the mass melt fraction is given by

\[ f = \left( e - c_{ps} T_m \right) / \lambda^o \] (13.2-43)

### 13.3 Method of Solution

#### 13.3.1 CLAP Initialization and Cladding Meltdown

The temperature and melt fraction of initial cladding are computed after the onset of boiling by the SAS fuel-pin model located in the subroutine TSHTRV and the calculation continues after CLAP initiation. This subroutine also contains the logical statements for CLAP initiation and cladding melt-through.

The first cladding to move is assumed to be the first axial segment that is completely molten; CLAP is initiated with this first melt-through. Any other axial segments join the molten cladding region if any one of its three radial segment nodes is molten; i.e., is above the liquidus temperature.
When entering CLAP (which uses coolant time steps) from a heat-transfer time step, a check is made to see whether any previously solid cladding nodes are now to be treated as molten cladding. If so, the total mass and energy of the initial, refrozen, and moving cladding are evaluated and these become the mass and energy of the moving cladding.

13.3.2  Solution of the Cladding Energy Equations

13.3.2.1  Interface with the Fuel-pin Model

There are slight differences in the thermodynamic representations of molten steel in the fuel-pin and CLAP models. In particular, the fuel-pin model in subroutine TSHTRV has a melting band (discrete solidus and liquidus temperatures) and a temperature-dependent specific heat, whereas CLAP has a single melting temperature and constant specific heats. If cladding temperatures from the fuel-pin model were used directly in CLAP calculations (for example, in adding segments to the molten region), then, possibly, energy would not be conserved due to differences in the thermodynamic models. To insure energy conservation, CLAP instead uses nodal energies rather than temperatures. A mean energy is computed from the SAS nodal energies:

\[ \bar{e}_j = \frac{1}{4} e_{1,j} + \frac{1}{2} e_{2,j} + \frac{1}{4} e_{3,j} \]  

(13.3-1)

where the \( e_{ij} \)'s are the energies of the three radial nodes in axial segment \( j \). CLAP then evaluates the intact-cladding temperature \( T_i \) and melt fraction using \( \bar{e} \) and Eqs. 13.2-41 to 13.2-43.

The fuel-pin model computes fuel temperatures in the molten cladding zone and both fuel and intact cladding temperatures for the remainder of the fueled section. For the molten zone, the CLAP routine integrates the fuel surface heat loss for each segment for a heat-transfer time interval:

\[ Q_j = P_j \Delta z_j \int_{t^*}^{t^*+\Delta t^*} \phi_{c,j} dt \]  

(13.3-2)

where

\[ \Delta z_j = z_{j+1} - z_j \]

\( t^* \) is time at start of current heat-transfer time step

\( \Delta t^* \) is current heat-transfer time interval

\( \phi_c \) is the heat flux given by Eq. 13.2-27

\( z_j \) is the elevation at the bottom of the "\( j \)"th segment.
This heat loss is utilized at the outer fuel boundary condition by the fuel-pin model. In a similar fashion, the heat loss from the outer surface of an intact cladding segment is computed by

\[
Q_j = P_v \Delta z_j \int_{r'}^{r'} \phi_{r,j} \, dt
\]  

(13.3-3)

where \(\phi\) is the heat flux from Eq. 13.2-30 or 13.2-37, depending upon the configuration. This heat loss becomes part of the outer cladding boundary condition in the fuel-pin model, being added to the coolant heat loss, if any.

### 13.3.2.2 Intact and Refrozen Cladding

For this configuration, we set \(\phi = 0\) (adiabatic outer boundary) in the refrozen cladding energy Eq. 13.2-23. The energy equation is then combined with Eqs. 13.2-30 and 13.2-41 to give

\[
\frac{dT_{s,j}}{dt} = \xi_1 (T_i - T_s) \bigg|_j
\]

(13.3-4)

where

\[
\xi_{1,j} = P_v k_v / \left[ A_s \rho_s c_{ps} (\Delta r_i + \Delta r_s) \right] \bigg|_j
\]

Since Eq. 13.2-23 has been reduced from a general field equation to a nodal equation, it becomes an ordinary differential equation (in time) in the process. The subscript \(j\), of course, denotes the axial segment number for which the parameter is evaluated.

Equation 13.3-4 is converted to an implicit finite difference equation by substituting for the left side, the following:

\[
\frac{dT_{s,j}}{dt} \approx \frac{\Delta T_{s,j}^n}{\Delta t}
\]

(13.3-5)

and by evaluating \(T_{s,j}\) on the right side at the advanced time

\[
T_{s,j}^{n+1} = T_{s,j}^n + \Delta T_{s,j}^n
\]

(13.3-6)

giving (after some rearrangement):

\[
\Delta T_{s,j}^n = \frac{\xi_1 (T_i - T_s) \Delta t}{1 + \xi_1 \Delta t} \bigg|_j^n
\]

(13.3-7)

The implicit form is used rather than an explicit solution because it is stable for large \(\xi_1\) (or small \(A_s\)) and a reasonably sized \(\Delta t\).
The heat flux $\phi_n$ required for the fuel-pin boundary condition (Eq. 13.3-3) is evaluated from the energy equation:

$$\Phi_{n,j} = \frac{A_s \rho_s C_{ps} \Delta T_j}{P_e \Delta t}$$

(13.3-8)

13.3.2.3 Evaluation of Convective Term in the Moving Cladding Energy Equation

The CLAP model uses a modified donor cell technique developed by Bohl [13-2] for the evaluation of the convective term

$$C_v = A_c \rho_c v \frac{\partial e_c}{\partial z}$$

(13.3-9)

in Eq. 13.2-20. This scheme uses a segment boundary mass flow $w^*$ which is estimated by

$$w_j^* = \frac{1}{2} \left[ A_{c,j-1} \rho_{c,j-1} v_{c,j-1} + A_{c,j} \rho_{c,j} v_{c,j} \right]$$

(13.3-10)

The flow direction is determined by a mean flow $w_m$:

$$w_{m,j} = \frac{1}{2} \left( w_j^* + w_{j+1}^* \right)$$

(13.3-11)

The recipe for the convective term for a unblocked segment is as follows

$$C_{v,j} = \frac{w_j^* e_{c,j} - e_{c,j+1}}{z_{m,j} - z_{m,j+1}}$$

for $w_{m,j} > 0, w_j^* > 0$

(13.3-12a)

$$C_{v,j} = \frac{w_{j+1}^* e_{c,j+1} - e_{c,j}}{z_{m,j+1} - z_{m,j}}$$

for $w_{m,j} < 0, w_{j+1}^* < 0$

(13.3-12b)

$$C_{v,j} = 0, \text{ otherwise}$$

(13.3-12c)

The parameter $z_{m,j}$ is the nodal elevation, which is related to the segment interface elevations $z_j$ by

$$z_{m,j} = \frac{1}{2} \left( z_j + z_{j+1} \right)$$

(13.3-13)
If the "j"th segment is nearly blocked, then the energy convection computed by Eq. 13.3-12 may be too large in magnitude. In this case, we define a segment flow $w_j$ as

$$w_j = A_{c,j} \rho_{c,j} v_{c,j}$$

and compute the convective terms by (blocked segment only)

$$C_{v,j} = w_j \frac{e_{c,j} - e_{c,j-1}}{z_{m,j} - z_{m,j-1}} \quad \text{for } w_{m,j} > 0, w_j > 0$$

$$C_{v,j} = w_j \frac{e_{c,j+1} - e_{c,j}}{z_{m,j+1} - z_{m,j}} \quad \text{for } w_{m,j} < 0, w_j > 0$$

$$C_{v,j} = 0, \quad \text{otherwise}$$

The scheme also suppresses convection (sets $C_v = 0$) if the adjoining donor cell (either $j-1$ or $j+1$ depending on the sign of $w_m$) is blocked.

13.3.2.4 Moving Cladding on Bare Fuel

The outermost radial fuel node in the fuel-pin model is duplicated in CLAP for axial segments within the molten zone. The outer fuel temperature in CLAP, $T_f$, is reset to the value computed by the pin model at the start of each heat-transfer time step. However, between heat transfer time steps, the fuel temperature is computed in CLAP; this is done primarily to achieve numerical stability, but it may also improve the accuracy of results. The configuration of the SAS outer fuel node and moving cladding is shown in Fig. 13.3-1. The transient heat-balance equation for this outer node is

$$\pi \left( r_{NR}^2 - r_{NT}^2 \right) \rho_f c_{pf} \frac{\partial T_f}{\partial t} + 2\pi k_f \frac{\partial T_f}{\partial r} \left| r_{NT} - \pi \left( r_{NR}^2 - r_{NT}^2 \right) Q_{NT} = -P_r h \left( T_f - T_c \right) \right.$$  \hfill (13.3-16)

where reference to axial core segment $j$ is tacitly implied.

It is assumed that the heat flow from the interior fuel nodes and the heat generated in the outer fuel node (given by the second and third terms in Eq. 13.3016) are relatively constant over one heat-transfer time step. We can therefore approximate these terms by evaluating them at the beginning of a heat-transfer time step. These terms are represented symbolically by the constant $C_f$ defined by

$$C_f = 2\pi k_f \frac{\partial T}{\partial r} \bigg|_{r_{NT}} - \pi \left( r_{NR}^2 - r_{NT}^2 \right) Q_{NT}, \text{ at } t = t^*$$  \hfill (13.3-17)

where $t^*$ is the beginning of the heat-transfer time step.
Because of the high heat-transfer coefficient to the molten cladding (Eq. 13.2-28), the fuel-surface temperature and molten cladding temperature are closely coupled. For that reason, the term representing the instantaneous heat loss to the molten steel (on the right side of Eq. 13.3-16) is retained as is, rather than incorporating it into the constant \( C_f \). Combining Eqs. 13.3-16 and 13.3-17 and rearranging, we have

\[
\frac{dT_{f,j}}{dt} + \gamma_f = -\xi_f \left( T_f - T_c \right)_j
\]  (13.3-18)

where

\[
\gamma_f = C_f \left[ \frac{\pi}{\rho} \left( r_{NR}^2 - r_{NT}^2 \right) \right] \rho_f c_{pf} \mid_j
\]  (13.3-19)

\[
\xi_f = P_f h \left[ \frac{\pi}{\rho} \left( r_{NR}^2 - r_{NT}^2 \right) \rho_f c_{pf} \right] \mid_j
\]  (13.3-20)

Combining Eqs. 13.2-20, 13.2-27, 13.2-42, and 13.3-9, one obtains the nodal energy equation for moving cladding:
\[
\frac{dT_{c,j}}{dt} + \gamma_{c,j} = \xi_2 (T_f - T_c)_j
\]  
(13.3-21)

where

\[
\gamma_{c,j} = C_v \left( A_r \rho_c c_{pc} \right)_j
\]  
(13.3-22)

\[
\xi_{2,j} = P_r h \left( A_r \rho c_{pc} \right)_j
\]  
(13.3-23)

Equations 13.3-18 and 13.3-21 are converted to time-implicit difference equations by approximating the time derivatives according to

\[
\frac{dT_{f,j}}{dt} \approx \frac{\Delta T_{f,j}^n}{\Delta t^n}
\]  
(13.3-24)

\[
\frac{dT_{c,j}}{dt} \approx \frac{\Delta T_{c,j}^n}{\Delta t^n}
\]  
(13.3-25)

and evaluating the temperatures on the right-hand side at the advanced time \( t^{n+1} \). After substituting

\[
T_{c,j}^{n+1} = T_{f,j}^n + \Delta T_{f,j}^n
\]  
(13.3-26)

\[
T_{c,j}^{n+1} = T_{c,j}^n + \Delta T_{c,j}^n
\]  
(13.3-27)

the two difference equations are solved simultaneously for \( \Delta T_f \) and \( \Delta T_c \) and second-order terms in \( \Delta t \) are discarded, with the following results

\[
\Delta T_{c,j}^n = -\frac{\left[ \xi_2 (T_f - T_c) - \gamma_c \right]_j}{1 + (\xi_2 + \xi_f)\Delta t}_j
\]  
(13.3-28)

\[
\Delta T_{f,j}^n = -\frac{\left[ \xi_f (T_f - T_c) - \gamma_f \right]_j}{1 + (\xi_2 + \xi_f)\Delta t}_j
\]  
(13.3-29)

The heat flux \( \phi_c \), which is needed to evaluate the integral in Eq. 13.3-2, is computed using a finite difference form of the moving clad energy Eq. 13.2-20:
\[ \phi_c = \frac{C_w}{P_r} + \frac{A_r \rho_c c_p \Delta T_c}{P_r \Delta t} \] (13.3-30)

### 13.3.2.5 Moving Cladding on Intact and Refrozen Cladding

The nodal energy equation for the moving cladding for this configuration is obtained by combining Eqs. 13.2-20, 13.2-32, 13.2-42, and 13.3-9, giving

\[ \frac{dT_{c,j}}{dt} + \gamma_c = \xi_2 (T_m - T_c) \] (13.3-31)

where \( \gamma_c \) and \( \xi_2 \) are defined in Eqs. 13.3-22 and 13.3-23.

Solving this equation implicitly, i.e., replacing \( T_c \) by the updated value, approximating the time derivative by Eq. 13.3-25, and solving for \( \Delta T_c \), we get

\[ \Delta T_{c,j}^n = -\left[ \frac{\xi_2 (T_m - T_c) - \gamma_c}{1 + \xi_2 \Delta t} \right]_j^n \] (13.3-32)

The equation for the refrozen cladding temperature is found by substituting Eqs. 13.2-30, 13.2-31, and 13.2-41 into the energy Eq. 13.2-23, resulting in

\[ \frac{dT_{s,j}}{dt} = \xi_3 (T_i - T_s) - \xi_3 (T_s - T_m) \] (13.3-33)

where

\[ \xi_3 = \frac{P k_c}{A_r \rho_c c_p \Delta r} \] (13.3-34)

Converting Eq. 13.3-33 to a finite-difference, implicit equation and solving for \( \Delta T_s \), one obtains

\[ \Delta T_{s,j}^n = -\left[ \frac{\xi_3 (T_i - T_s) - \xi_3 (T_s - T_m)}{1 + \xi_3 \Delta t} \right]_j^n \] (13.3-35)

The heat fluxes \( \phi_r \) and \( \phi_{hf} \) are required for the fuel-pin boundary conditions (Eq. 13.3-3) and to evaluate the rate of melting (Eq. 13.2-25). These are evaluated using discretized versions of the energy Eqs. 13.2-20 and 13.2-23 after computing \( \phi_r \) from Eq. 13.2-30. Then \( \phi_{hf} \) is computed using Eq. 13.2-24.

Several constraints apply to \( \phi_{hf} \). For positive \( \phi_{hf} \) (melting), more cladding cannot melt than actually exists in a frozen state. This restriction can be expressed as

\[ \text{Constraints} \]
\[
\phi_{hf} \leq \frac{A_e \rho_e \lambda_e}{\Delta t P_r}
\]  
(13.3-36)

In case \( \phi_{hf} \) is adjusted to satisfy Eq. 13.3-36, new values of \( \phi_c, \phi_r \) and \( \phi_f \) are computed from discretized versions of energy Eqs. 13.2-20 and 13.2-23, along with Eq. 13.2-24, the definition of \( \phi_{hf} \).

The constraint for negative \( \phi_{hf} \) (freezing) arises from the condition that more cladding cannot freeze than exists in the molten state. Expressed mathematically, the limit is

\[
\phi_{hf} \geq -\frac{A_e \rho_e \lambda_e}{\Delta t P_r}
\]  
(13.3-37)

### 13.3.2.6 Intact and Moving Cladding

The molten cladding energy equation for this case is identical to that for the case of moving cladding on intact and refrozen cladding. The molten cladding temperature change is therefore given by Eq. 13.3-32, which is also displayed below

\[
\Delta T_{c,j}^n = -\left[\frac{\xi_2 (T_m - T_c) - \gamma_c \Delta t}{1 + \xi_2 \Delta t}\right]_{j}^n
\]  
(13.3-38)

The quantities \( \phi_1, \phi_2, \) and \( \phi_{trial} \) are computed from Eqs. 13.2-34 to 13.2-36. Then \( \phi_{hf} \) and \( \phi_r \) are computed according to Eq. 13.2-37, which we repeat below

\[
\phi_{hf} = 0, \phi_r = \phi_2 \quad \text{for } \phi_{trial} \geq 0,
\]  
(13.3-39a)

\[
\phi_{hf} = \phi_{trial}, \phi_r = \phi_1 \quad \text{for } \phi_{trial} < 0.
\]  
(13.3-39b)

The case of \( \phi_{trial} \geq 0 \) corresponds to melting of the initial cladding; the heat of fusion is included in \( \phi_r \) which is the negative of the heat flux to the pin surface.

For \( \phi_{trial} \leq 0 \), we obtain a negative \( \phi_{hf} \) (freezing) which will result in the appearance of refrozen cladding during the current time step. The constraint given by Eq. 13.3-37 is checked and, if not satisfied, then (i) \( \phi_{hf} \) is set equal to the limit given by Eq. 13.3-37 and (ii) a new \( \phi_r \) is computed by

\[
\phi_r = \phi_2 + \phi_{hf}
\]  
(13.3-40)
13.3.2.7 Heat Loss to Structure

At the onset of cladding motion, the structure is still relatively cool and consequently constitutes a potentially significant heat sink for the refreezing of cladding, particularly in small experimental subassemblies. The local heat absorbed by the structure (per unit length and unit time) is given by

\[ Q_{s,j}^n = \frac{\theta P_w(T_m - T_w)}{\Delta r_w / k + 1/h} \]  

(13.3-41)

where

- \( \theta \) = multiplier on heat loss to structure (usually = 1)
- \( P_w \) = heated perimeter of the structure
- \( T_w \) = structure temperature
- \( \Delta r_w \) = half-thickness of structure.

The present CLAP model allows for the indirect transfer of heat form the moving cladding to the structure by way of the frozen cladding. An adjustment to the refrozen clad temperature \( \Delta T_s \) is defined by

\[ T_{s,j}^{n+1} = \hat{T}_{s,j}^{n+1} + \hat{\Delta}T_{s,j} \]  

(13.3-42)

where \( \hat{T}_{s,j}^{n+1} \) is the unadjusted refrozen cladding temperature.

Normally, the temperature adjustment would be given by

\[ \Delta T_{s,j}^n = Q_s \frac{\Delta t}{A_s \rho_s c_{ps}} \frac{1}{a_j} \]  

(13.3-43)

However, this formulation would be unstable in the case of vanishing \( A_s \) or large \( \Delta t \). To achieve stability, we slightly alter the physics; in particular, \( T_m \) is replaced in Eq. 13.3-41 by \( T_{s,j}^{n+1} \). This adjustment in \( T_s \) is made only for segments where moving cladding is present; and, for these segments, we would expect the frozen cladding temperature to be close to the melting temperature, and hence the error in this approximation would be small. With this modification the adjustment is given by

\[ \Delta T_{s,j}^n = \frac{\xi_w \Delta t^n (\hat{T}_{s,j}^{n+1} - T_w)}{1 + \epsilon_w \Delta t^n} \]  

(13.3-44)

where
\[ \xi_w = \left( \frac{\theta P_w}{A_s \rho_s C_{ps} \left( \frac{\Delta r_w}{k} + \frac{1}{k} \right)} \right)^n \]  

(13.3-45)

### 13.3.3 Refrozen Steel Area Calculation

The refrozen cladding mass conservation Eq. 13.2-21 with the source term given by Eq. 13.2-25 is rewritten in the form

\[ \rho \frac{\partial A_s}{\partial t} = - \frac{P_{hf} \rho}{\lambda} - A_s \frac{\partial \rho_s}{\partial t}. \]  

(13.3-46)

The finite difference form of this equation is

\[ A_{s,j}^{n+1} = A_{s,j}^n - \left[ \frac{\phi_{hf} P_{r}}{\lambda} \Delta t \right]^n_{j} + A_{s,j}^n \left( \rho_{s,j}^{n+1} - \rho_{s,j}^n \right) \rho_{s,j}^{n+1} \]  

(13.3-47)

After the density \( \rho_{s,j}^{n+1} \) is evaluated from \( T_{s,j}^{n+1} \) using Eq. 13.2-38, then the area \( A_{s,j}^{n+1} \) is computed using Eq. 13.3-47. The thickness of the refrozen steel layer is computed from its area by assuming that the refrozen steel forms an annular ring around the intact cladding.

### 13.3.4 Moving Cladding Area Calculation

The continuity Eq. 13.2-12 and source term (Eq. 13.2-25) are rewritten as

\[ \rho_c \frac{\partial A_c}{\partial t} = -A_c \frac{\partial \rho_c}{\partial t} - C_a + \frac{P_{r} \phi_{hf}}{\lambda} \]  

(13.3-48)

where

\[ C_a = \frac{\partial}{\partial z} (\rho_c A_c v_c) \]  

(13.3-49)

The finite difference form of this equation is given by

\[ A_{c,j}^{n+1} = A_{c,j}^n + \left[ -A_{c,j}^n \left( \rho_{c,j}^{n+1} - \rho_{c,j}^n \right) - C_a \Delta t_n + \frac{P_{r} \phi_{hf} \Delta t}{\lambda} \right]_{j}^{n} \rho_{c,j}^{n+1} + A_{mod,j}^n \]  

(13.3-50)

where \( A_{mod} \) is a correction term, defined later.
The solution method uses donor-cell differencing to evaluate the convective term \( C_a \) in terms of the nodal fluxes \( w_j \) (see Eq. 13.3-14) and nodal elevation (see Eq. 13.3-13). Normally \( A_{mod} = 0 \) and \( C_a \) is computed as follows

\[
C_a = \frac{w^n_j - w^n_{j-1}}{z_{m,j} - z_{m,j-1}} \quad \text{for} \ w_{m,j} \geq 0 \tag{13.3-51a}
\]

\[
C_a = \frac{w^n_{j+1} - w^n_j}{z_{m,j+1} - z_{m,j}} \quad \text{for} \ w_{m,j} < 0 \tag{13.3-51b}
\]

Modifications to this formulation are made (i) to prevent cladding transfer outside of the fuel and blanket region and (ii) to inhibit cladding transfer to flooded or blocked nodes; the modifications consist simply of setting the appropriate values of \( w_j \) equal to zero.

Additionally, adjustments must be made for the case where the molten cladding area exceeds the available area \( A_{max} \) defined by

\[
A^{n+1}_{max,j} = A^{n+1}_{f,j} - A^{n+1}_{c,j} - A^{n+1}_{s,j} \tag{13.3-52}
\]

where

\[
A_f = \text{total area for cladding allowed by the fuel}
\]

\[
A_i = \text{area of the intact cladding (if any)}.
\]

For the case where the computed \( A^{n+1}_{c,j} \) exceeds \( A_{max} \), the following steps are taken: (i) the condition is flagged by setting \( NFULL_j = 1 \) (initial value is 0), (ii) the molten cladding area \( A^{n+1}_{c,j} \) is set equal to \( A_{max} \) and (iii) the computed area for the donor segment is later adjusted consistent with step (ii).

To accomplish step (iii), we first estimate the volume of cladding convected into segment \( j \), denoted by \( \Gamma_j \), from continuity considerations:

\[
\Gamma_j \approx \left[ A^{n+1}_{max,j} - A^n_{c,j} - \frac{P_r \Phi_h \Delta t}{\rho_{c,j} \Delta t} \right] \cdot (z_{j+1} - z_j) \tag{13.3-53}
\]

Rather than adjusting \( C_a \) for the donor cell, we instead set \( w_j \) (or \( w_{j+1} \)) equal to zero and compute a correction \( A_{mod} \), which is the area change (negative) due to the volume of fluid \( \Gamma_j \) transferred to the flooded cell. For example, for the case of the donor cell below the flooded cell we have
\[ w_j = 0, \ A_{\text{mod},j-1}^n = -\Gamma_j / (z_j - z_{j-1}) \text{ for } NFULL_j = 1, \ w_{m,j-1} \geq 0. \] 
\[ \text{(13.3-54)} \]

Similarly, for the case of the donor cell above the flooded cell we have

\[ w_{j+1} = 0, \ A_{\text{mod},j+1}^n = -\Gamma_j / (z_{j+2} - z_{j+1}) \text{ for } NFULL_j = 1, \ w_{m,j+1} < 0. \] 
\[ \text{(13.3-55)} \]

### 13.3.5 Reactivity Calculation

The reactivity change due to cladding relocation is computed by

\[ \Delta K = \sum_j (m_j^n - m_j^o) \cdot W_j \] 
\[ \text{(13.3-56)} \]

where
- \( m_j^n \) = mass of cladding in the \( j \) th segment
- \( m_j^o \) = original mass of cladding in the \( j \) th segment
- \( W_j \) = cladding reactivity worth distribution.

In the molten region, the mass is computed by

\[ m_j^n = A_c \rho_c \Delta z_j^n \] 
\[ \text{(13.3-57)} \]

where \( \Delta z_j = z_{j+1} - z_j \) \[ \text{(13.3-58)} \]

Outside the molten region the mass is evaluated using

\[ m_j^n = m_j^0 + A_s \rho_s \Delta z_j^n + A_c \rho_c \Delta z_j^n. \] 
\[ \text{(13.3-59)} \]

Due to roundoff and other possible small errors, the total mass of cladding may not be absolutely conserved which, if left uncorrected, would create anomalous reactivity effects. To insure mass conservation, the computed mass distribution is renormalized by the following steps:

\[ M^n = \sum_j m_j^n, \] 
\[ \text{(13.3-60)} \]

\[ M^o = \sum_j m_j^o, \] 
\[ \text{(13.3-61)} \]
\[ m_j^n \cdot M^n / M^n \rightarrow m_j^n \]  

(13.3-62)

where the operation \( A \rightarrow B \) indicates that \( A \) is substituted for \( B \).

### 13.3.6 Moving Cladding Velocity Calculation

The cladding momentum equation is solved in a separate subroutine (TSCLD2) that is called after the coolant dynamics equations have been solved. The terms \( \partial p / \partial z \) and \( F_v \) in the cladding momentum equation are evaluated at time \( t^n + 1/2 \Delta t^n \) (by averaging values at \( t^n \) and \( t^{n+1} \)) to achieve maximum accuracy with respect to sodium-vapor-induced cladding accelerations.

The pin friction term, \((\partial p / \partial z)_{fr}\), is evaluated at the end of the time step to obtain maximum stability under conditions of strongly accelerating thin cladding films. Substituting

\[ v_{c,j}^{n+1} = v_{c,j}^n + \Delta v_{c,j}^n \]  

(13.3-63)

into Eqs. 13.2-15 and 13.2-16 and retaining only linear terms, we obtain an equation of the form

\[ F_{p,j}^{n+1} = y_{1,j}^n + y_{2,j}^n \Delta v_{c,j}^n \]  

(13.3-64)

where

\[ y_{1,j}^n = \frac{32 \mu_c v_c}{D_c^2} \bigg|_j \quad \text{for } Re_j^n < (Re)_{break} \]  

(13.3-65)

\[ y_{2,j}^n = \frac{32 \mu_c}{D_c^2} \bigg|_j \quad \text{for } Re_j^n < (Re)_{break} \]  

(13.3-66)

\[ y_{1,j}^n = \frac{b_j \rho_c v_c}{2D_c} \bigg|_j \quad \text{for } Re_j^n \geq (Re)_{break} \]  

(13.3-67)

\[ y_{2,j}^n = \frac{b_j \rho_c v_c}{D_c} \bigg|_j \quad \text{for } Re_j^n \geq (Re)_{break} \]  

(13.3-68)

The parameter \( C_m \) is used to represent the momentum convective term.
\[ C_{m,j} = v_c \frac{\partial v_c}{\partial z} \bigg|_j \]  

Equation (13.3-69)

This parameter is evaluated by alternative formulae depending upon whether the segment is filled with cladding. For \( NFULL(j)=1 \), indicating a filled segment, the term is estimated by the formula

\[ C^n_{m,j} = v^n_{c,j} \frac{\partial v^n_c}{\partial z} \bigg|_{n+1/2} \]  

Equation (13.3-70)

where the derivative \( \frac{\partial v^n_c}{\partial z} \) is obtained by rearranging the continuity equation:

\[ \frac{\partial v^n_c}{\partial z} = \frac{1}{\rho^n c A^n} \left[ \frac{\phi^n h P^n_y}{\lambda^n} - \frac{\partial (\rho^n c A^n)}{\partial t} - v^n_c \frac{\partial (\rho^n c A^n)}{\partial z} \right] \]  

Equation (13.3-71)

and evaluating at time \( t^n + 1/2 \Delta t^n \). Two alternative equations are obtained, one for each flow direction, as given by the following:

\[ \left. \frac{\partial v^n_c}{\partial z} \right|_{n+1/2} = \frac{1}{(\rho^n c A^n)_{c,j}} \left[ \frac{\phi^n h P^n_y}{\lambda^n} \right]_{j} - \rho^n_{c,j} A^n_{c,j} - A^n_{c,j} \left( \rho^n_{c,j+1} A^n_{c,j+1} - A^n_{c,j} \right) d^n_{c,j} \]  

Equation (13.3-72)

for \( w^n_{m,j} < 0 \)

\[ \left. \frac{\partial v^n_c}{\partial z} \right|_{n+1/2} = \frac{1}{(\rho^n c A^n)_{c,j}} \left[ \frac{\phi^n h P^n_y}{\lambda^n} \right]_{j} - \rho^n_{c,j} A^n_{c,j} - A^n_{c,j} \left( \rho^n_{c,j+1} A^n_{c,j+1} - A^n_{c,j} \right) d^n_{c,j} \]  

Equation (13.3-73)

for \( w^n_{m,j} \geq 0 \)

where quantities on the right-hand side of Eqs. 13.3-72 and 13.3-73 with the superscript \( n+1/2 \) are evaluated at time \( t^n + \Delta t^n/2 \) as follows

\[ ( )^{n+1/2} = 1/2 \left[ ( )^n + ( )^{n+1} \right] \]  

Equation (13.3-74)

For \( NFULL_i=0 \), indicating an unblocked segment, we use the identity
\[ \frac{v_c \partial v_c}{\partial z} = \frac{1}{2} \frac{\partial v_c^3}{\partial z} \]  

(13.3-75)

and evaluate the momentum convection term as follows

\[ C_{m,j} = \frac{1}{2} \left[ \left( v_{c,j+1}^n \right)^2 - \left( v_{c,j-1}^n \right)^2 \right] / \left( z_{m,j+1} - z_{m,j} \right) \text{ for } v_{m,j}^n < 0 \]  

(13.3-76)

\[ C_{m,j} = \frac{1}{2} \left[ \left( v_{c,j}^n \right)^2 - \left( v_{c,j-1}^n \right)^2 \right] / \left( z_{m,j} - z_{m,j-1} \right) \text{ for } v_{m,j}^n \geq 0 \]  

(13.3-77)

The discretized version of the moving-cladding momentum (Eq. 13.2-19), using the linear approximation for \( F_p \) (Eq. 13.3-64), and the symbolic representation for the momentum convective term (Eq. 13.3-69), is given by

\[
\left( \rho_{c,j} \right)^{n+1/2} \left[ \frac{\Delta v_{c,j}^n}{\Delta t^n} + C_{m,j} + g \right] = - \frac{\partial P}{\partial z}_{ij}^{n+1/2} - \frac{A_{v}}{A_{c}} F_{v}^{n+1/2} - y_{1,j}^{n} - y_{2,j}^{n} \Delta v_{c,j}^{n} - \begin{cases} 0 & \text{if freezing} \\ P_{r,j}^{n} \phi_{h,f,j}^{n} \left( v_{c,j}^{n} + \Delta v_{c,j}^{n} \right) & \text{if melting} \end{cases}
\]  

(13.3-78a)

\[
A_{c,j}^{n+1/2} \lambda_{c,j}^{n} \right) 
\]

(13.3-78b)

Solving this equation for \( \Delta v_{c} \), one obtains the form used in the CLAP program.

### 13.4 Input-Output Description

A listing of CLAP-related input variables is given in Table 13.4-1 as an aid in preparing or modifying SAS input decks. Additionally, the input items on this list should be rechecked when problems are encountered in the running of SAS cases with cladding motion. This list contains all input items used directly by the following CLAP subroutines: TSCLD1, TSCLD2, SODFRC and DENSIT and, in addition, input items used to initiate CLAP and to calculate reactivity effects due to cladding motion (in subroutine FEEDBK).

The CLAP output appears with both the main full printout and the boiling printout. A sample output is shown in Figure 13.4-1. The output labels are generally self-explanatory. The Fortran variable and units corresponding to each output item are given in Table 13.4-2.
Table 13.4-1. Listing of CLAP-Related Input Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Reference Eq. No.</th>
<th>Reference</th>
<th>Block</th>
<th>Location</th>
<th>Recommended Values</th>
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</thead>
<tbody>
<tr>
<td>$T_{\text{ref}}$</td>
<td>13.2-38</td>
<td>TR</td>
<td>13</td>
<td>419</td>
<td>1700 K</td>
</tr>
<tr>
<td>$T_m$</td>
<td>---</td>
<td>TESOL*</td>
<td>13</td>
<td>810-812</td>
<td>1700 K [13-7]</td>
</tr>
<tr>
<td>$\lambda^o$</td>
<td>13.2-43</td>
<td>UEMELT</td>
<td>13</td>
<td>816-818</td>
<td>2.703x10^5 J/kg [13-7]</td>
</tr>
<tr>
<td>$\lambda^o$</td>
<td>13.2-43</td>
<td>UEMELT</td>
<td>13</td>
<td>816-818</td>
<td>2.703x10^5 J/kg [13-7]</td>
</tr>
<tr>
<td>$C_{ps}$</td>
<td>13.2-41</td>
<td>CE</td>
<td>13</td>
<td>1070-1072</td>
<td>690.1 J/kg K [13-7]</td>
</tr>
<tr>
<td>$W_j$</td>
<td>13.3-56</td>
<td>CLADRA</td>
<td>62</td>
<td>160-183</td>
<td>-</td>
</tr>
<tr>
<td>$\rho_s^o$</td>
<td>13.2-38</td>
<td>DENS</td>
<td>63</td>
<td>35</td>
<td>7.256x10^3 kg/m^3† [13-7]</td>
</tr>
<tr>
<td>$C_{1,2,3}$</td>
<td>13.2-28</td>
<td>C1, C2, C3</td>
<td>64</td>
<td>3-5</td>
<td>Eq. 13.2-28 [13-8]</td>
</tr>
<tr>
<td>AFRV,BFRV</td>
<td>13.2-5</td>
<td>AFRV, BFRV</td>
<td>64</td>
<td>168, 169</td>
<td>0.316, -0.25</td>
</tr>
<tr>
<td>$\rho_c^o$</td>
<td>13.2-39</td>
<td>DENS</td>
<td>65</td>
<td>3</td>
<td>6.98x10^3 kg/m^3† [13-7]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>13.2-38</td>
<td>AE</td>
<td>65</td>
<td>4</td>
<td>2.3x10^-5/K† [13-7]</td>
</tr>
<tr>
<td>$C$</td>
<td>13.2-39</td>
<td>RHOCD</td>
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<td>5</td>
<td>8.3x10^-5/K† [13-7]</td>
</tr>
<tr>
<td>$\mu_m$</td>
<td>13.2-18a</td>
<td>VISM C</td>
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<td>6</td>
<td>6.42x10^-3 Pa·s [13-7]</td>
</tr>
<tr>
<td>$\mu_r$</td>
<td>13.2-18b</td>
<td>VISTR</td>
<td>65</td>
<td>7</td>
<td>1x10^4 Pa·s [13-3]</td>
</tr>
<tr>
<td>$\mu_k$</td>
<td>13.1-18c</td>
<td>VISSC</td>
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</tr>
<tr>
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<td>13.2-18b</td>
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<td>$b_r$</td>
<td>13.2-16b</td>
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<td>65</td>
<td>10</td>
<td>0.02 [13-3]</td>
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<td>$(\text{Re})_{\text{break}}$</td>
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<td>REBRK</td>
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<td>11</td>
<td>2100. [13-3]</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>13.2-10</td>
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<td>65</td>
<td>12</td>
<td>75.0 [13-5]</td>
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<tr>
<td>$\alpha_{\text{crit}}$</td>
<td>13.2-10</td>
<td>ALPHCR</td>
<td>65</td>
<td>13</td>
<td>0.0 [13-5]</td>
</tr>
<tr>
<td>$(\text{fps})_o$</td>
<td>13.2-11</td>
<td>FPSO</td>
<td>65</td>
<td>14</td>
<td>0.3s</td>
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<td>$x$</td>
<td>13.2-11a</td>
<td>EXPFPS</td>
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<td>15</td>
<td>3.0</td>
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<td>$\theta$</td>
<td>13.3-41</td>
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<td>17</td>
<td>1.0</td>
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<tr>
<td>$a$</td>
<td>13.2-18a</td>
<td>AVISC</td>
<td>65</td>
<td>20</td>
<td>5492 K [13-7]</td>
</tr>
<tr>
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<td>13.2-42</td>
<td>CPC</td>
<td>65</td>
<td>21</td>
<td>621.7 J/kg K† [13-7]</td>
</tr>
</tbody>
</table>

*Originally TME, but TME is now set equal to the solidus temperature TESOL.
†Evaluated at the melting temperature of 1700 K.
Table 13.4-2. Summary of CLAP Output Items

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>FORTRAN Variable</th>
<th>Units</th>
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<tr>
<td>CLAP Time Step Count</td>
<td>n</td>
<td>ICOUNT</td>
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<tr>
<td>Axial Coolant Mode</td>
<td>j</td>
<td>J</td>
<td>-</td>
</tr>
<tr>
<td>Main Axial (Nodal) Elevation</td>
<td>zm,j</td>
<td>ZFM</td>
<td>m</td>
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<tr>
<td>Refrozen Cladding Thickness</td>
<td>2Δrₚ</td>
<td>RCLAD1</td>
<td>m</td>
</tr>
<tr>
<td>Moving Cladding Thickness</td>
<td>2Δrₜ</td>
<td>TCLAD1</td>
<td>m</td>
</tr>
<tr>
<td>Intact Cladding Temperature</td>
<td>Tᵢ</td>
<td>TCLAV</td>
<td>K</td>
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<tr>
<td>Refrozen Cladding Temperature</td>
<td>Tₛ</td>
<td>TEMFS1</td>
<td>K</td>
</tr>
<tr>
<td>Moving Cladding Temperature</td>
<td>Tₖ</td>
<td>TEMMC1</td>
<td>K</td>
</tr>
<tr>
<td>Moving Cladding Velocity</td>
<td>Vₖ</td>
<td>CVEL1</td>
<td>m/s</td>
</tr>
<tr>
<td>Coolant Flow Area</td>
<td>Aᵥ</td>
<td>AREAC1</td>
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</tr>
<tr>
<td>Internal Flag</td>
<td></td>
<td>LVEL</td>
<td>-</td>
</tr>
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</table>
(=1 in molten zone, =0 otherwise)
### Table: Sample CLAP Output

<table>
<thead>
<tr>
<th>COOLANT NO</th>
<th>AXIAL MODE</th>
<th>AXIAL ELEVATION</th>
<th>CLAD THICKNESS</th>
<th>REFROZEN CLAD THICKNESS</th>
<th>MOVING CLAD</th>
<th>INTACT CLAD</th>
<th>REFROZEN TEMPERATURES</th>
<th>MOVING TEMPERATURES</th>
<th>COOLANT FLOW</th>
<th>CLAD VELOCITY</th>
<th>COOLANT MASS</th>
<th>INTERNAL FLAGS</th>
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</tbody>
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**Fig. 13.4-1 Sample CLAP Output**
REFERENCES


The SAS4A/SASSYS-1 Safety Analysis Code System