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IRIS Scaling Analysis
Part I

Westinghouse

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Part I

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FOREWORD

This document, IRIS Scaling Analysis Part I covers Stage 1 (System Decomposition) and 2 (Scale Identification) of the Hierarchical, Two-Tired Scaling Analysis.

Stage 3 (Top-Down System Scaling Analysis) and 4 (Bottom-Up Process Scaling Analysis) will be submitted as Part 2 and Part 3 respectively.

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NOMENCLATURE

List of Symbols

A_{ik} area for transfer between "i" and "k" constituents

$D = \left(\Pi_m - \Pi_p\right)/\Pi_p$ distortion in the model

j_{ik} flux between "i" and "k" constituents

Q_i volumetric flow rate of constituent "i"

S_i distributed sources per unit volume of constituent "i"

t time

u_i internal energy of constituent "i"

$\vec{v}_i$ velocity of constituent "i"

V_i volume occupied by constituent "i"

Greek Letters

α_i volume fraction of constituent "i"

$\Delta[Q_i\psi_i] = [Q_i\psi_i]_{in} - [Q_i\psi_i]_{out}$ convection term

$\Pi^{ik} = \dfrac{j_{ik}A_{ik}}{Q_i\psi_i}$ specific time ratio for transient process between constituens "i" and "k"

$\Pi_{ki} = \dfrac{\psi_i\alpha_i}{\psi_k\alpha_k}\omega_{ik}^S\tau_k$ characteristic time ratio

Π_m model characteristic time ratio

Π_p prototype characteristic time ratio

$\Pi^{si} = \dfrac{S_i}{Q_i\psi_i}$ specific time ratio for the distributed source term within control volume of constituent "i"

ρ_i density of constituent "i"

$$\tau_i = \frac{V_i}{Q_i}$$ residence time of constituent "i"

$$\psi_i = \rho_i,\ \rho_i \vec{v}_i,\ \rho_i u_i$$ conserved property of constituent "i" per unit volume

$$\omega_{ik}^{S} = \frac{j_{ik} A_{ik}}{V_i \psi_i}$$ specific frequency of constituent "i" interacting with constituent "k"

List of superscripts

+	dimensionless
S	specific

List of subscripts

0	at $t = 0$, initial conditions

List of subscripts and superscripts

$$
\left[
\begin{array}{l}
\text{Automatic Depressurization System} \\
\text{bulk} \\
\text{bubble} \\
\text{Constituent Cavity(Pool)} \\
\text{annulus} \\
\text{Core} \\
\text{cylindrical rods} \\
\text{carbon steel} \\
\text{Condenser Vessel} \\
\text{Containment Volume} \\
\text{Downcomer} \\
\text{structures}
\end{array}
\right] \quad \text{(a,c)}
$$

iv

i constituent "i"

(a,c)

ik between "i" and "k" constituents

k constituent "k"

(a,c)

(a,c)

mass   mass

momentum   momentum

$$\left[\begin{array}{l} \text{Nitrogen} \\ \text{out of the control volume} \\ \text{plenum} \\ \text{Pipe lines connecting Emergency Heat Removal System Heat Exchanger and Steam Generator} \\ \text{pipe} \\ \text{plenum} \\ \text{pool} \\ \text{Pipe lines connecting Steam Generator and Emergency Heat Removal System Heat Exchanger} \\ \text{Pump Suction Plenum} \\ \text{Pressure Suppression System} \\ \text{Nitrogen Tank} \\ \text{Pool} \\ \text{Vent and Sparger System} \\ \text{Pressurizer} \\ \text{primary cooler} \\ \text{Reactor Coolant Pump} \\ \text{Integral Reactor Coolant System} \\ \text{riser} \\ \text{fuel rods} \\ \text{solid} \\ \text{Reactor Coolant} \end{array} \right]^{(a,c)}$$

$$\begin{bmatrix} \text{Steam Generator Annular Space} \\ \text{Steam Generator Central Column} \\ \text{shell} \\ \text{stainless steel} \\ \text{cladding} \\ \text{secondary water} \\ \text{tube} \\ \text{water} \\ \text{wire} \end{bmatrix}^{(a,c)}$$

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1.0 Scaling methodology – Introduction to Hierarchical, Two-Tiered Scaling Analysis

The scaling analysis will be a part of Transient and Accident Analysis Methods (according to "Elements of Evaluation Model Development and Assessment Process - EMDAP" - see, Staudenmeier, 2002). Portions of the EMDAP procedure where scaling analysis is applied are highlighted in Figure 1.1.

The Hierarchical, Two-Tiered Scaling (H2TS) Analysis Methodology (see Zuber, 1991) will be applied for the IRIS System. The methodology uses concepts from the hierarchical theory presented by Mesarovic et al., 1970 and the concept of time-scale modeling used to analyze large power systems (presented in Chow, 1986).

The H2TS methodology generates quantitative results useful for technical management of the projects. It can obtain a proper balance between experimentation and computer code application by establishing priorities for experiments, test facility design and operation and for computer code development, validation and uncertainty quantification. It can also establish a procedure for performing efficient and adequate technical reviews.

The Hierarchical Two-Tiered Scaling Analysis Methodology is based on characteristic time ratios, which can be established for each transfer process that occurs between the constituents of a system. The characteristic time ratio
a) combines the temporal and spatial scales of the transfer process and of the system, and
b) provides a quantitative measure for evaluating the effect of the transfer process on the system.

The hierarchical structure and the characteristic time ratios provide dimensionless similarity groups and, by comparing their numerical values, priorities can be established for preserving similarity groups between a test facility and the actual components.

The same procedure can be used to identify and prioritize the physico-chemical processes which should be modeled in the computer codes simulations, and to identify important parameters for code sensitivity calculations and code uncertainty qualification.

Figure 1.2 presents the flow diagram with the four elements of the H2TS methodology.

The physical decomposition of the system is carried out in the first stage (see Stage 1 in Figure 1.2) of the methodology. Three classes of scales (measures) need to be identified at the beginning of the scaling analysis. The amounts of constituents (or their concentrations) present in the system is one class. The second class is spatial (geometrical) and temporal (initial conditions and time sequences of the events affecting the system) characteristics of the system. The third class is concerned with the various transfer processes.

ELEMENT 1 – ESTABLISH REQUIREMENTS FOR EVALUATION MODEL CAPABILITY
1. Establish analysis purpose, transient class and power plant class
2. Specify figures of merit
3. Identify systems, components, phases, geometries, fields and processes that should be modeled
4. Identify and rank phenomena and processes

ELEMENT 2 – DEVELOP ASSESSMENT BASE
5. Specify objectives for assessment base
6. Perform scaling analysis and identify similarity criteria
7. Identify existing data and/or perform IETs and SETs to complete data base
8. Evaluate effects of IET distortions and SET scaleup capability
9. Determine experimental uncertainties

ELEMENT 3 – DEVELOP EVALUATION MODEL
10. Establish EM development plan
11. Establish evaluation model structure
12. Develop and/or incorporate closure models

ELEMENT 4 – ASSESS EVALUATION MODEL ADEQUACY
Closure Relations (Bottom-up)
13. Determine model pedigree and applicability
14. Prepare input and perform calculations to assess model fidelity and accuracy
15. Assess scalability of models

Integrated EM (Top-down)
16. Determine capability of field equations and numeric solutions
17. Determine applicability of EM to simulate system components
18. Prepare input and perform calculations to assess system interactions
19. Assess scalability of integral analyses and data for distortions
20. Determine EM biases and uncertainties

ADEQUACY DECISION
Does code meet adequacy Standard?

NO - Return to appropriate elements, make and assess corrections
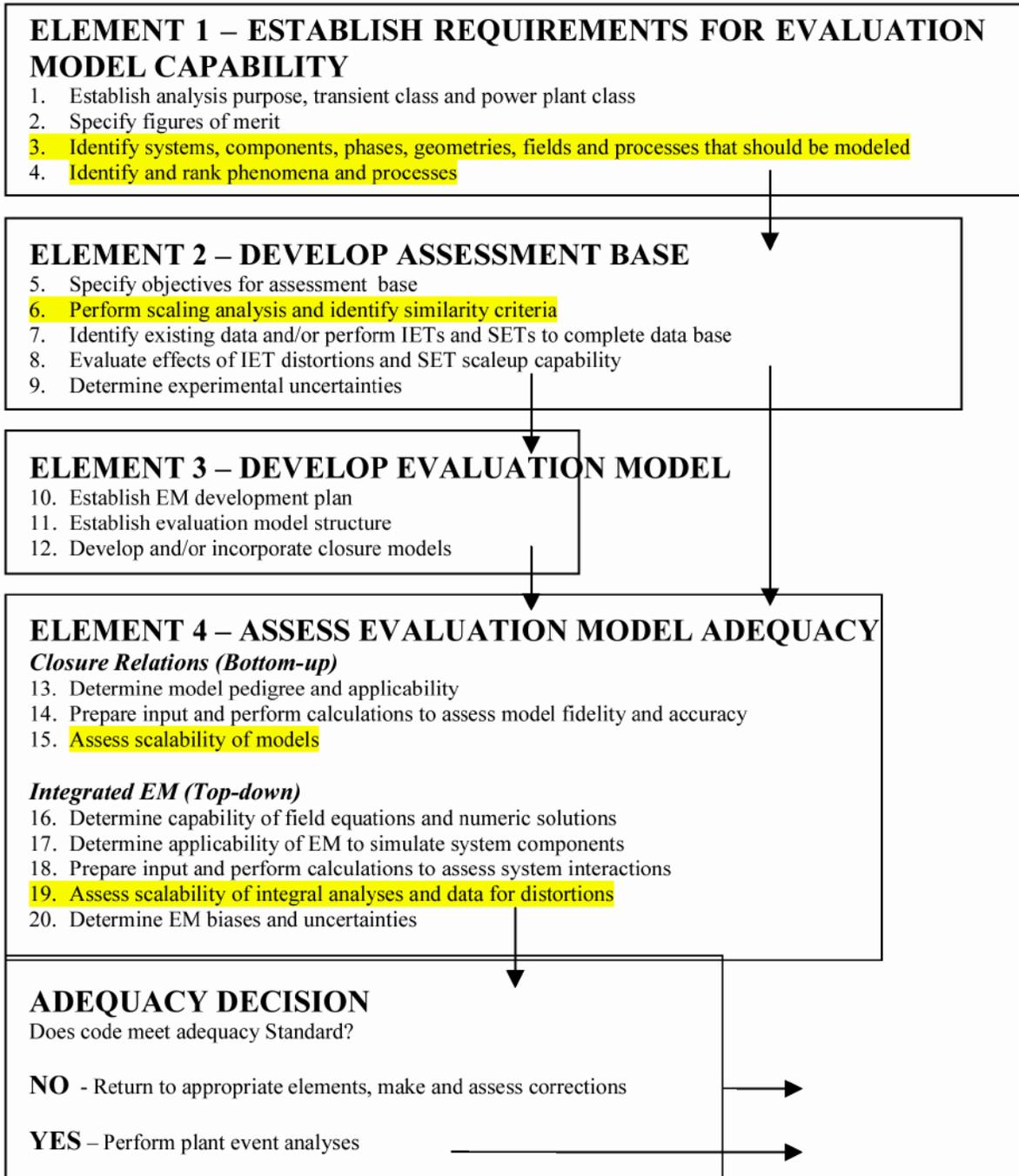
YES – Perform plant event analyses

Figure 1.1   Scaling analysis as a part of Transient and Accident Analysis Methods (according to "Elements of Evaluation Model Development and Assessment Process - EMDAP" - see, Staudenmeier, 2002)

Flow Diagram for Hierarchical, Two-Tiered Scaling Analysis

Stage 1 SYSTEM DECOMPOSITION	Stage 2 SCALE IDENTIFICATION	Stage 3 TOP-DOWN SYSTEM SCALING ANALYSIS	Stage 4 BOTTOM-UP PROCESS SCALING ANALYSIS
PROVIDE: System hierarchy **IDENTIFY:** Characteristic: • Concentrations • Geometries, initial conditions and time sequences of the events • Transfer Processes	**PROVIDE HIERARCHY FOR:** Volumetric concentrations Area concentrations Residence times Process time scales	**PROVIDE:** Conservation equations **DERIVE:** Scaling groups and Characteristics time ratios **ESTABLISH:** Scaling hierarchy **IDENTIFY:** Important process to be addressed in bottom-up process scaling analyses	**PERFORM:** Detailed scaling analysis for important local processes **DERIVE AND VALIDATE:** Scaling groups

Figure 1.2   Flow Diagram for Hierarchical, Two-Tiered Scaling Analysis (from Zuber, 1991)

The hierarchies for the three classes are established in the second stage of the methodology (see Stage 2 in Figure 1.2). A spatial and temporal scale that relates each constituent to the system needs to be defined. Also, two spatial scales and two temporal scales need to be associated with each transfer process to account for the effects on two different media (constituents, or phases) separated by the same transfer area, but occupying two different volumes and having different flow rates.

The third stage (see Stage 3 in Figure 1.2) of the H2TS methodology is Top-Down System Scaling Analysis. After providing the adequate conservation equations, the scaling groups and characteristics time ratios can be calculated. Then, the scaling hierarchy and identification of the important processes to be addressed in the last stage (see Stage 4 - Bottom-Up scaling analyses in Figure 1.2) can be obtained.

The H2TS method is used to develop sets of specific and characteristic time ratios for the transfer processes.

The control volume balance equation for constituent "i" is

$$\frac{dV_i\psi_i}{dt} = \Delta[Q_i\psi_i] \pm \sum_{k=1}^{m-1}(j_{ik}A_{ik}) + S_i$$

where

$\Delta[Q_i\psi_i] = [Q_i\psi_i]_{in} - [Q_i\psi_i]_{out}$ is convection term

$\psi_i = \rho_i, \rho_i\vec{v}_i, \rho_i u_i$ is conserved property per unit volume

V_i volume occupied by constituent "i"

Q_i volumetric flow rate of "i"

j_{ik} flux between "i" and "k" constituents

A_{ik} area for transfer between "i" and "k"

S_i distributed sources per unit volume

Or in dimensionless form

$$\tau_i\frac{dV_i^+\psi_i^+}{dt} = \Delta[Q_i^+\psi_i^+] \pm \sum_{k=1}^{m-1}(\Pi_{ik}j_{ik}^+A_{ik}^+) + \Pi_{si}S_i^+$$

where

$$V_i^+ = \frac{V_i}{V_{i,0}}, \psi_i^+ = \frac{\psi_i}{\psi_{i,0}}, Q_i^+ = \frac{Q_i}{Q_{i,0}}, j_{ik}^+ = \frac{j_{ik}}{j_{ik,0}}, A_{ik}^+ = \frac{A_{ik}}{A_{ik,0}}, S_i^+ = \frac{S_i}{S_{i,0}}$$

$\tau_i = \dfrac{V_{k,0}}{Q_{k,0}}$ is residence time of constituent "i"

$\Pi_{ik} = \dfrac{j_{ik,0}A_{ik,0}}{Q_{i,0}\psi_{i,0}}$ is specific time ratio for transient process between constituens "i" and "k"

$\Pi_{si} = \dfrac{S_{i,0}}{Q_{i,0}\psi_{i,0}}$ is specific time ratio for the distributed source term within control volume

Each specific time ratio is composed of a specific frequency and residence time constant

$$\Pi_{ik} = \frac{j_{ik,0}A_{ik,0}}{Q_{i,0}\psi_{i,0}} = \left(\frac{j_{ik,0}A_{ik,0}}{V_{i,0}\psi_{i,0}}\right)\left(\frac{V_{i,0}}{Q_{i,0}}\right) = \omega_{ik}^S\tau_i$$

where

$$\omega_{ik}^{S} = \frac{j_{ik,0} A_{ik,0}}{V_{i,0} \psi_{i,0}} \text{ is specific frequency.}$$

The characteristic time ratio can be expressed as a function of both constituents.

$$\Pi_{ki} = \frac{j_{ki,0} A_{ki,0}}{Q_{k,0} \psi_{k,0}} = \left(\frac{j_{ki,0} A_{ki,0}}{V_{k,0} \psi_{k,0}} \right) \left(\frac{V_{k,0}}{Q_{k,0}} \right) = \omega_{ki}^{S} \tau_k = \left(\frac{\psi_{i,0} \alpha_{i,0} V \omega_{ik}^{S}}{\alpha_{k,0} V \psi_{k,0}} \right) \tau_k = \frac{\psi_{i,0} \alpha_{i,0}}{\psi_{k,0} \alpha_{k,0}} \omega_{ik}^{S} \tau_k$$

where

$$j_{ki,0} A_{ki,0} = j_{ik,0} A_{ik,0} = Q_{i,0} \psi_{i,0} \left(\frac{V_{i,0}}{Q_{i,0}} \right) \omega_{ik}^{S} = \psi_{i,0} \alpha_{i,0} V \omega_{ik}^{S}$$

and

$\alpha_{i,0}, \alpha_{k,0}$ are volume fractions of "i" and "k" constituens.

Time ratios represent the total change of a conserved property in the control volume, during the residence time, caused by the relevant transfer process.

If the time ratio is small $(\Pi \ll 1)$ only a small quantity of the corresponding property would be transferred in the specified available time. As a consequence the specific process would not be important to the overall transient.

If the time ratio is large $(\Pi \gg 1)$ the specific process has a high transfer rate of the conserved property during the residence time period. The larger the time ratio the more important is the transfer process.

Time ratios will be used to establish a hierarchy and ranking for various processes. The characteristic time ratio must be preserved for the prototype and the model $(\Pi_m = \Pi_p)$.

The effect of a distortion in the model can be estimated from $D = (\Pi_m - \Pi_p)/\Pi_p$.

The characteristics time ratios combine the system and process point of view for each transfer process, and provide a quantitative measure to evaluate the relevance of a process. The characteristics time ratio incorporates the effects of the three scales (the amount of material present in the system, geometry, and time). Two characteristics time ratios are associated with each transfer area and they quantify the effect of the transfer process on the two media separated by the transfer area.

The Top-Down System Scaling Analysis considers the interactions between the constituents and their overall effects on the system. It enhances the efficiency of the scaling methodology by identifying important processes affecting the behavior of the whole system.

The Bottom-Up Scaling Analysis is the fourth element (see Stage 4 in Figure 1.2) of the H2TS methodology. It focuses on the important processes and on the performance of the isolated parts of the system. A detailed scaling analysis of the important processes, derivation and validation of the scaling groups, ensures the prototypicality of the test data. The Bottom-Up Scaling Analysis provides the sufficiency of the scaling methodology.

Scaling analysis will be performed based on the previous experience gained during AP600 and AP1000 licensing. Among the referenced documents, WCAP-14812, Revision 2, and WCAP-14845, Revision 3, are relevant to the AP600 Containment scaling. WCAP-15613 is related to AP1000 Containment licensing. Scaling methodology for primary and secondary loop components in AP600 is presented in WCAP-14727 Revision 2. NUREG/CR-6731 will be used as well as a basis for IRIS primary and secondary loop components scaling analysis inside the Reactor Pressure Vessel.

Scaling for an IRIS integral test must be performed simultaneously for both Reactor Pressure Vessel and Containment components because of the important interactions between them.

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2.0 Stage 1 – System Decomposition

A physically based decomposition establishes a hierarchical architecture for the system.

The process is exemplified in Figure 2.1. The system (S) can be subdivided into subsystem components (SS). Each subsystem can be built of several modules (M). Various constituents (C) (in fact materials) as water, steel, concrete etc., can be inside the modules. Some constituents may be in several phases (P). For example, water could be in the liquid, or gas phase. Each phase could be present in various geometrical configurations (G). For example, liquid phase of water could be in the shape of droplets, liquid films near the vertical walls, ponds/pools and bulk coolant flowing stream. Various fields (F) and corresponding equations (for mass, momentum and energy balance) can be considered for each geometrical configuration. The complexity of the equations depends on the processes acting on the particular geometrical configuration. For example, to calculate the energy balance of the water droplet surrounded by the mixture of air and steam we might take into consideration processes of convection around the droplet surface, evaporation or condensation on the droplet surface, as well as heat conduction and convection inside the droplet volume.

The example in Figure 2.1 shows how a system can be decomposed and the hierarchy of the components established. Using this approach for the all IRIS systems, subsystems and modules (presented in Figure 2.2 and Table 2.1) the results reported in Figure 2.3 are obtained.

SYSTEM (S)	S	for example IRIS Engineered Safeguard Features (ESF)							
SUBSYSTEM (SS)	SS_1	for example Pressure Supression System (PSS)					.	SS_K	
MODULES (M)	M_1	for example Pool (PSS_POOL)				M_2			
CONSTITUENTS (C)	C_1	for example water			..	C_K			
PHASES (P)	g	l liquid			s				
GEOMETRICAL CONFIGURATIONS (G)	G_1	G_2 droplets		.	G_K				
FIELDS (F)		M	MM	Energy					
PROCESSES				P_1 evaporation					
				P_2 convection					
				P_3 conduction					

Figure 2.1 An Example of the System Decomposition and Hierarchy

(a,c)

Figure 2.2 IRIS Subsystems and Modules

Table 2.1 IRIS Systems, Subsystems and Modules

IRIS Systems	IRIS Subsystems	(a,c)
Integral Reactor Coolant System (RCS)	(1) DOWNCOMER (DC) (2) LOWER PLENUM (LP) (3) CORE (CORE) (4) RISER (RIB) (5) PUMP SUCTION PLENUM (PSP) (6) PUMP (RCP) (7) PRESSURIZER (PZR) (8) STEAM GENERATOR (SG) (9) STEAM GENERATOR ANNULAR SPACE (SGAS) (10) STEAM GENERATOR CENTRAL COLUMN (SGCC) (11) DIRECT VESSEL INJECTION LINE (DVI)	
Engineered Safeguard Features (ESF)	(12) EMERGENCY BORATION TANK (EBT) (13) AUTOMATIC DEPRESSURIZATION SYSTEM (ADS) (14) LONG TERM GRAVITY MAKEUP SYSTEM (1) – PIPE LINES CONNECTING SUPPRESSION POOL AND REACTOR VESSEL (LGMS1) (15) LONG TERM GRAVITY MAKEUP SYSTEM (2) – PIPE LINES CONNECTING REACTOR VESSEL CAVITY AND DIRECT VESSEL INJECTION LINE (LGMS2) PRESSURE SUPPRESSION SYSTEM (PSS) *IRIS Modules* (16) POOL (PSS_POOL) (17) NITROGEN TANK (PSS_NT) (18) VENT AND SPARGER SYSTEM (PSS_VENT_SP) EMERGENCY HEAT REMOVAL SYSTEM (EHRS) *IRIS Modules* (19) EMERGENCY HEAT REMOVAL SYSTEM HEAT EXCHANGER (EHRS_HX) (20) REFUELING WATER STORAGE TANK (LGMS_RWST) (21) STEAM GENERATOR MAKE UP TANK (EHRS_SGMT) (22) PIPE LINES CONNECTING STEAM GENERATOR AND EHRS HEAT EXCHANGER (?_SG_EHRS_HX) (23) PIPE LINES CONNECTING LOWER PLENUM AND STEAM GENERATOR (?_EHRS_HX_SG)	
Containment Vessel (CV)	(24) CONTAINMENT VOLUME (CNVOL) (25) CONTAINMENT CAVITY POOL (CAV)	

[ ]^(a,c)

Figure 2.3 consists of [   ]$^{(a,c)}$ panels. Each panel is for one subsystem, or module. The schematic of the IRIS systems with the marked position of the corresponding subsystem or module is presented above each table. The table specifies the list of constituents (materials) present in the subsystem or module, phases (liquid, vapor or solid), geometrical configurations, field equations and processes to be scaled.

The specified constituents (materials) are all possible materials that might be present in the subsystem or module at any time during the postulated accident. [For example, nitrogen is not present at the beginning of the accident in the reactor coolant system. However, it might be present in the upper portions of the reactor coolant system at the end of the accident due to the steam condensation on the steam generator surfaces and inflow of the steam and nitrogen mixture (see panels 4 to 10) into the reactor vessel from the containment (the IRIS containment is nitrogen inerted for hydrogen control in severe accidents scenarios).

]$^{(a,c)}$

The phases of the water (liquid water and steam) might be in various geometrical configurations. For the purpose of scaling, if the configuration is continuous, the presence of the bulk liquid or bulk steam is indicated. On the other extreme, if the configuration is dispersed, the presence of droplets or bubbles is specified.

In reality some intermediate geometrical configurations might exist (like agglomerated bubbles, or gas plugs inside the pipes). [For the sake of simplicity however only bulk or dispersed configurations are considered here.

]$^{(a,c)}$

In the case of solid phase (in most cases either carbon steel or stainless steel) the geometrical configurations are shells, structures or pipes.

Field equations of mass, momentum and energy need to be taken into consideration for the constituents in liquid or gas phases. [In some cases, as for the reactor coolant system volume and containment volume the pressure response equation need to be considered as well.

]$^{(a,c)}$

[The transient energy equations for the solid bodies need to be considered so that effects of the stored energy releases or effects of the energy accumulation can be taken into consideration.

]$^{(a,c)}$

At the end of the table (last row) the processes to be scaled are specified for each constituent (material).

(a,c)

Figure 2.3 IRIS Breakdown and Hierarchy

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3.0 Stage 2 – Scale Identification

The purpose of the second stage is to provide hierarchy for the volumetric concentrations, area concentrations, residence times and process time scales. The results are presented in the form of panels for each IRIS subsystem/module (see Figure 3.1 - IRIS Scale Identification panels [   ]$^{(a,c)}$).

The volumes of each constituent (material), each phase and each geometrical configuration ($V_{constituent}, V_{phase}, V_{geometrical\ configuration}$) need to be specified.

By knowing the volumetric flow rates Q for each constituent (material), phase and geometrical configuration the corresponding residence times can be calculated as $\tau_{constituent} = V_{constituent}/Q_{constituent}$, $\tau_{phase} = V_{phase}/Q_{phase}$ and $\tau_{g.config} = V_{g.config.}/Q_{g.config.}$.

An area concentration of the geometrical configuration ($A_{(g.config.1),(g.config\ 2)}/V_{g.config.1}$) is specified by the area between two geometrical configurations divided by the volume of the corresponding geometrical configuration.

Process times of interest are specific frequencies and specific time ratios, defined below.

The specific frequencies for mass, momentum and energy transfer ($\omega^s_{mass}, \omega^s_{momentum}, \omega^s_{energy}$) can be calculated from mass flux, momentum flux, energy flux and area concentrations between two geometrical configurations. Also, density, velocity and internal energy of the corresponding geometrical configuration need to be known.

The specific time ratios for mass momentum and energy transfer ($\Pi^{mass}, \Pi^{momentum}, \Pi^{energy}$) are defined as the product of the specific frequencies by the residence times.

In most situations it was assumed that dispersed configurations (droplets or bubbles) are surrounded only by the continuous configuration (bulk steam or bulk liquid) and interactions of the dispersed configurations with the solid surfaces are neglected.
[

          ]$^{(a,c)}$

In the case of solid phase the release (or accumulation) of the stored energy from (into) the solid bodies is the only process of interest. Since the volumetric flow rate of the solid bodies is equal to zero, the residence time and specific time ratios are not calculated.
[   ]$^{(a,c)}$
More details will be given during the next stage (Stage 3 Top-down scaling), when energy transfer equations for the solid bodies will be presented.

Figure 3.1 IRIS Scale Identification

(a,c)