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⟨Technical Note⟩

Development of a Computer Code, CONPAS, for an Integrated Level 2 PSA

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Abstract

A PC window-based computer code, CONPAS (CONtainment Performance Analysis System), has been developed to integrate the numerical, graphical, and results-operation aspects of Level 2 probabilistic safety assessments (PSA) for nuclear power plants automatically. As a main logic for accident progression analysis, it employs a concept of the small containment phenomenological event tree (CPET) helpful to trace out visually individual accident progressions and of the detailed supporting event tree (DSET) for its detailed quantification. For the integrated analysis of Level 2 PSA, the code utilizes five distinct, but closely related modules. Its computational feasibility to real PSAs has been assessed through an application to the UCN 3&4 full scope Level 2 PSA. Compared with other existing computer codes for Level 2 PSA, the CONPAS code provides several advanced features: (1) systematic uncertainty analysis / importance analysis / sensitivity analysis, (2) table / graphical display & print, (3) employment of the recent Level 2 PSA technologies, and (4) highly effective user interface. The main purpose of this paper is to introduce the key features of CONPAS code and results of its feasibility study.

1. Introduction

A Level 2 PSA deals with how the accident sequences leading to severe core damage can progress further and lead to the containment failure, which would result in a significant release of radioactive fission products to the environment, i.e., source term. The resultant risk is measured as the frequency of a source term release from the containment [1]. In this stage, a containment phenomenological event tree (CPET, CET) is typically utilized to develop the range of possible accident progression paths, containment failure modes, and radionuclide source term release categories. By the event tree model, inter-dependent physico-chemical processes and the availabilities of containment systems are logically traced, that are relevant to the integrity of the containment. These components consist of event paths which chronologically characterize the various possibilities of accident progressions within containment and probabilities assigned to each component expressing its impact on each accident. Then the overall quantification process of CPET produces conditional probabilities for each accident path, originating from a plant damage state (PDS) which includes a set of initial conditions for Level 2 PSA, and ending at a source term category (STC) which indicates containment failure modes and related source term characteristics to the environment. The final results of Level 2 PSA are summarized as the occurrence frequencies of STCs and, if exist, their uncertainties. In order to systematically integrate these procedures for Level 2 PSA and associated information, it is essentially required to utilize an accident progression analysis code.

Since the CET approach was initially applied in the WASH-1400 [2], the above procedures have been formalized and computerized in various way; the NUREG-1150 APET approach [3] and EVNTRE code [4], the S-CET (SCET) approach [5,6] and ETA-II (ET-LOAD) code [7,8], the APSET approach [9] and ETAP code [10], the CET/PFT approach [11] and CAFTA code [12], the CET/DET approach [13] and NUCAP+ code [14], and RISKMAN using a modularized CET approach [15]. Their key features were critically compared in the previous paper [16]. In the viewpoint of CET structure, one major difference between NUREG-1150 approach and the other approaches is the number of top events. That is, the number of APET top events has been reduced for clarity - from about a hundred questions to about twenties or less. All important phenomenological issues in the NUREG-1150 APETs that are not represented in the CET top events are retained in the supporting logic trees or modeled externally to assure model completeness. In the viewpoint of computerization, on the other hand, all these codes for performing the Level 2 PSA have two weakpoints: One is that most of the existing codes do not have an explicit function for uncertainty quantification which is one of essential parts of Level 2 PSA. The only exception is the case of EVNTRE code which is developed for a large and complex CET analysis. The other is that most of the existing codes are developed under the DOS environment and so their availability may be limited under the coming Windows environment. From the above two reasons, there happens need to develop the new type of PSA software which meets PSA analysts' demands for the application of PSA new field.

Most recently, a PC window-based computer code, CONPAS, has been developed to perform effectively an integrated Level 2 PSA and to overcome these limits of the existing codes for Level 2 PSA [17]. As a main logic for accident progression analysis, the CONPAS code employs a concept of the small containment phenomenological event tree (CPET) helpful to trace out visually individual accident progressions and of the detailed supporting event trees (DSETs) for its quantification. In the approach, three types of main trees and two types of supporting trees are utilized: PDS event tree for PDS categorization and system event tree (SET) extended to containment systems for its quantification, CPET for accident progression analysis and DET for its quantification, and STC event tree for STC grouping. All these trees are then linked by using event classification logic rules and the quantified outcomes are obtained. The approach for containment or accident progression analysis produces not only a scrutable and understandable model of containment failure mechanisms and enough details to analyze important factors for containment responses to severe accidents, but also a flexible and concise

Table 1. Key Characteristics of CONPAS Compared with the Existing Level 2 PSA Codes

Code Name	Source	Approach for Accident Progression	O/S	Key Characteristics
EVNTRE	USNRC	APET (accident progression event tree)	DOS	General CET (very large size) Uncertainty quantification Use of parameters within CET
RM-ETA(a)	PLG	(conventional containment event tree)	DOS OS/2	General CET (large size) Links tree modules
ETA-II / ET-LOAD	EPRI	S-CET/SCET (simplified containment event tree)	DOS	Accident specific CET(medium size) Sensitivity analysis
ETAP	JAERI	APSET (accident progression stage event tree)	DOS	General CET(Large size) Use of accident stage-wised trees Importance analysis
CAFTA(b)	EPRI	CET/PFT (CPET/phenomenological fault tree)	DOS	General CPET(medium size) Quantification by support tree(PFT)
NUCAP+	HNUS	CET/DET (CPET/ decomposition event tree)	DOS	General CPET (medium size) Quantification by support tree (DET) Importance / sensitivity analysis
CONPAS	KAERI	CET/DET (CPET/decomposition event tree)	MS Window	General CPET (medium size) Quantification by support tree (DET) *Internal calculation of CFP(c) by parameters* *Highly convenient user-interface* *Uncertainty / importance / sensitivity analysis*

Note: (a) = one module of RISKMAN
(b) = one element of EPRI's IPE Technical Assistance Package
(c) = containment failure probability for each failure mode

containment response model so that addition or elimination of new events for potential containment improvements is relatively easy. Table 1 shows key characteristics of CONPAS compared with the existing computer codes for Level 2 PSA. As shown in Table 1, the CONPAS code provides the several advanced features like systematic uncertainty analysis, importance analysis, and sensitivity analysis. In addition, it is characterized by the highly friendly user-interface, based on the windows environment. The major emphasis of this paper is on the key features of the CONPAS code and the utilized approaches.

The general description of CONPAS code system is given in Section 2, including code structures, major functions, and related approaches. In Section 3, a result of real application through a comparative assessment with the existing code is given for code validation and verification. Final conclusion of this paper is given in Section 4.

2. Description of the CONPAS Code System

As shown in Fig.1, CONPAS utilizes five distinct, but closely related modules for an integrated Level 2 PSA: (a) *ET Editor* for preparing the constituent

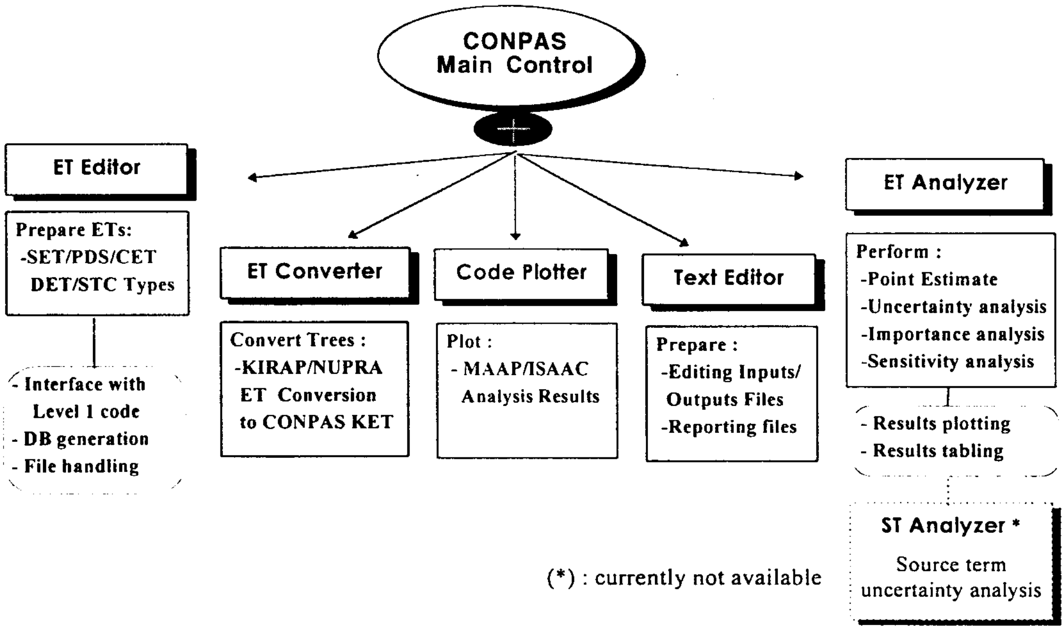

Fig. 1. General Structure of CONPAS Code System

event tree models describing accident progressions systematically, (b) *ET Analyzer* for analyzing quantitatively the prepared event trees and displaying graphically the resultant numerical outputs, and (c) auxiliary supporting modules (*ET Converter* for converting the ETs prepared by another codes into CONPAS specific ET, *Mechanistic Code Plotter* for utilizing the results obtained from severe accident analysis codes, and *Text Editor* for preparing the input decks for quantification and utilizing the calculational results). Key characteristics of each module are summarized in Table 2 and they are sequentially described in this section.

2.1. ET Editor Module

The module is used to prepare five distinct, but closely related tree structures: PDS event tree for PDS categorization and system event tree (SET) extended to containment system for its quantification, CPET for accident progression analysis and DET for its quantification, and STC event tree for STC grouping. In the quantification stage mentioned in the subsequent section, all these trees are inter-linked by using event classification logic rules. The logical flow of information between each trees is illustrated in Fig.2.

As shown in Fig.2, core melt sequences extended to the PDS level are grouped by a PDS event tree whose quantification is made by using the corresponding SETs. Frequencies for SET endpoints can be directly imported from Level 1 PSA codes through sequence information files generated by the editor automatically or inputted by users. In this stage, PDS event classification logic rules are assigned to each PDS event heading, which logically specify SET sequences corresponding to each PDS branch. All SET sequence frequencies are quantified from the fault tree analysis of Level 1 PSA. Next, a general CPET is constructed, which is based on importance of phenomenological events highly

Table 2. Key Functions of Each CONPAS Module

MODULES	KEY FEATURES	COMMENTS
ET Editor	<u>**ET Preparation and Level 1 PSA Interface**</u> • Edition ET Logic Diagram : SET,PDS,CET,DET,STC • Automatic Calculation of Sequence Probabilities : PDS, CET, STC • Use of Event Classification Rules for Quantification : PDS, CET, STC • Multiple Editions of ETs and Multiple Printing at One Time • Several ET Screen View & Printing Options • Availability of MS ACCESS for Database Utilization • Built-in Calculation of Containment Failure Probabilities • Interface with Level 1 PSA Code : KIRAP	Common use of Level 1 & Level 2 PSA
ET Analyzer	<u>**ET Quantification and Results Processing**</u> **Point Estimate Calculation : Tree Input Utilization** • PDS, CET, STC point values • Composite CET construction **Uncertainty Quantification :** Statistical Sampling • Latin Hypercube Sampling (LHS) & Monte Carlo Sampling • Input Distribution Types (1) Frequency Distribution Data -User distribution, Lognormal, Normal, Uniform, Loguniform (2) Uncertainty data given in the form of Experts Opinions - Deterministic Propagation - Propagation of Experts Opinions weighted by Probabilities (3) Parameter Values for Cont. Failure Probability Calculation - User distribution, Lognormal, Normal, Uniform, Loguniform • Utilization of Correlation Factors **Importance Analysis :** Risk Matrix Utilization • Importance of Initiators to PDS & STC • Importance of Level 1 Sequences to PDS & STC • Importance of PDS & CET Sequences to STC • Sequence Types to Events in Each Tree **Sensitivity Analysis :** Risk Matrix Utilization • Sensitivity of Initiators to PDS & STC • Sensitivity of PDS Sequence to STC **Processing of Quantified Results** • Generation of Statistical Parameters for Uncertainty • Results of Importance Analysis : Pie & Box plot • Results of Uncertainty Analysis : Line & Box plot (log/linear scale)	
Code Plotter	<u>**Processing of MAAP/ISAAC code Analysis Results**</u> • Multiple Sequences plot per each page • Multiple Variables plot per each page	Common use of Level 1 & Level 2 PSA
ET Converter	<u>**ET Conversion**</u> • Conversion of NUPRA/KIRAP ETs into CONPAS ETs	Common use of Level 1 & Level 2 PSA
Text Editor	<u>**Input/Output Processing**</u> • Results of Uncertainty / Importance / Sensitivity Analysis • Preparation of Uncertainty Input Deck	

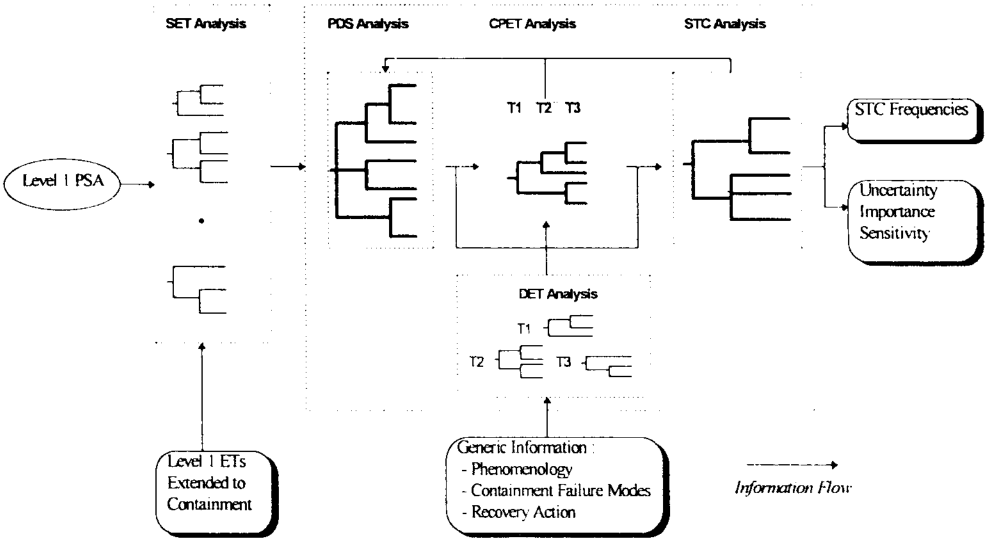

Fig. 2. Information Flow Between Event Trees Used in CONPAS

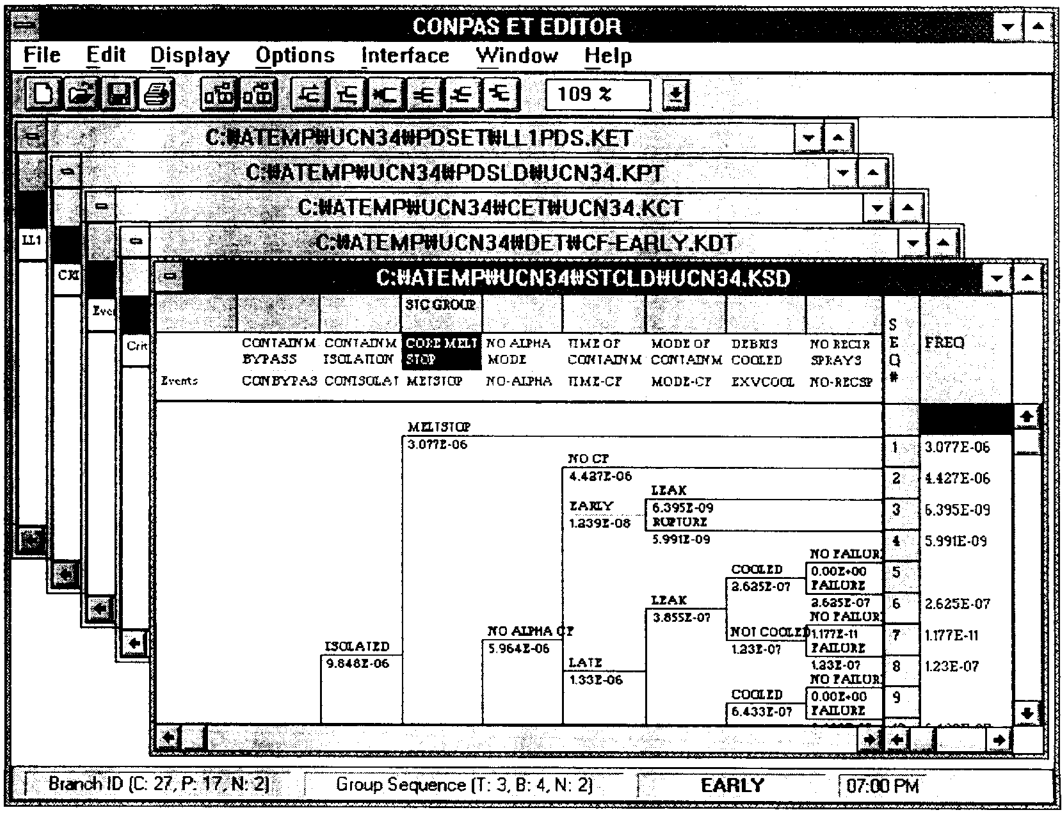

Fig. 3. ET Editor Screen Display for Five Types of Event Trees Considered in CONPAS

Table 3. Sample Event Classification Logic Rules

PDS Rule	DET Rule	STC Rule
RULE FOR PDS EVENT VESL	RULE FOR DET EVENT RCSP	RULE FOR STC EVENT SGTR
IF A:LLOCA=FAIL*A:HPR=SUCCESS;	IF P:VESL=ON*P:CSR=ON;	IF C:RCSFAIL=SGTR;
IF A:LLOCA=FAIL*A:LPR=SUCCESS;	THEN LOW;	THEN SGTR;
IF A:MLOCA=FAIL*A:HPR=SUCCESS;	IF P:VESL=FAILED*P:CSR=FAILED;	IF C:RCSFAIL=NO FAIL;
IF A:MLOCA=FAIL*A:LPR=SUCCESS;	THEN HIGH;	THEN NO SGTR;
THEN ON;	DEFAULT MEDIUM;	IF C:INVCOOL=NO COOL;
DEFAULT FAILED;		THEN NO SGTR;
		IF C:INVCOOL=COOL;
		THEN NO SGTR;

impacting on overall containment performance and source term. All inputs for quantifying the constructed CPET are given to the corresponding DETs which include a more detailed set of events that cause the occurrence of the CPET event. In this stage, DET event classification logic rules are assigned to the required DET event heading, which logically specify DET sequences corresponding to each CPET branch. While PDS rules specify dependencies between SET sequences and PDS branches, DET rules describe inter-dependencies between PDS, DET sequences, and prior CPET branches As the result, there exists only a unique CPET quantified to each PDS. Finally, a general STC event tree is constructed to analyze the source term and associated frequencies. In the stage, STC event classification logic rules are assigned to each STC event heading, which connect the CPET endpoints to the corresponding STC branches. As given in Table 3, all the event classification logic rules to be used in CONPAS are given in the form of 'IF-THEN-ELSE'. Fig.3 shows the typical types of event trees constructed by the module.

2.2. ET Analyzer Module

Main function of the module is to combine the five types of event trees constructed by ET Editor module. As the result, the quantified PDS, CET, and STC are generated in the form of event trees. In order to quantify the intermediate or final results, all these trees are linked in this module by using event classification logic rules. Four types of quantification can be done in this module: (a) point estimate, (b) importance analysis, (c) sensitivity analysis, (d) uncertainty analysis. Basic approach for the analyses and related main features are described below.

2.2.1. General Procedure for Quantification

In general, a quantitative risk analysis of nuclear power plants can be made by a well-known matrix formula [18,19],

$$\begin{aligned} \phi^P &= \phi^I \mathbf{M} \\ \phi^S &= \phi^P \mathbf{C} = \phi^I \mathbf{MC} \\ \phi^X &= \phi^S \mathbf{S} = \phi^P \mathbf{CS} = \phi^I \mathbf{MCS} \end{aligned} \tag{1}$$

where $\boldsymbol{\phi}^I$= initiating event vector, $\boldsymbol{\phi}^P$= PDS vector, $\boldsymbol{\phi}^S$= STC vector, $\boldsymbol{\phi}^X$= Risk vector, $\mathbf{M}$ = plant matrix, $\mathbf{C}$ = containment matrix, and $\mathbf{S}$ = consequence matrix.

Then the final risk can be obtained by the following procedure;

Step 1. Construction of the initiating event frequency vector extended to the containment, Φ^{I}. In general, the quantification is made by Level 1 fault /event tree analysis.

Step 2. Construction of the plant systems matrix of conditional probabilities, **M**. The matrix is based on the relative contribution (or conditional probabilities) of initiating event to PDS.

Step 3. Calculation of the PDS frequencies, $\Phi^{P} = \Phi^{I}\mathbf{M}$

Step 4. Construction of the containment matrix of conditional probabilities, **C**. The matrix is based on the relative contribution (or conditional probabilities) of PDS to STC.

Step 5. Calculation of the vector of release category frequencies, $\Phi^{S} = \Phi^{P}\mathbf{C}$

Step 6. Construction of consequence matrix, **S**, i.e., mean magnitude of consequence to the given STC.

Step 7. Calculation of risk vector by integration of previous steps, $\Phi^{X} = \Phi^{S}\mathbf{S}$.

Step 1, Step 2, and step 5 indicate an interface with Level 1 and Level 2 PSA, initial conditions of Level 2 PSA, and an interface with Level 2 and Level 3 PSA, respectively. Because the steps 6 and 7 are beyond the scope of Level 2 PSA, the present paper focuses on only Step 1 through step 5. Based on the above procedure, the CONPAS specific accident progression quantification is simply made up of three steps: PDS quantification by SETs, CPET quantification by the quantified PDS and DETs specified in the CPET top headings, and STC quantification by the quantified PDS and quantified CPETs for each PDS. This means that the PDS must be quantified to analyze the CPET in advance. In the same manner, the CPETs for each PDS must be quantified to analyze the STC in advance. As mentioned previously, all the quantifications are made by interpretating the event classification logic rules assigned to PDS, DET, and STC, which is an essential part of the present accident progression logic using the support event trees. For a consistent accident progression analysis, DETs should satisfy the following logical requirements: (a) DET endpoint outcomes match the CPET event being decomposed, (b) The selected DET sub-events can be quantified with available data or information, and (c) All dependencies in the DET sub-events on PDS conditions and prior CPET branch points are rigorously treated.

On the other hand, there are two options for PDS quantification : One is to assign PDS number to all the related SET sequences directly and the other is to utilize PDS event classification logic rules. After quantification, all the PDS and STC numbers are automatically returned to the endpoints of constituent SETs and quantified CPETs, respectively. The process makes it possible to identify the logical consistency between quantified trees (e.g. PDS and CPET) and the related supporting trees (e.g. SETs and DETs).

2.2.2. Importance/Sensitivity Analysis

Eq.(1) provides a verified means to identify the dominant contributors to the specified outcomes. To evaluate the relative contribution of event vector to the intermediate results, a diagonal matrix of Φ, whose diagonal elements are the values of Φ, is constructed. Each row of the right hand side of Eq.(1) consists of elements which are the contributions of each element of Φ to the results. For example, the relative importance of i-th PDS to j-th STC can be evaluated by

$$\mathrm{Imp}(\phi_j^s:\phi_i^p) = \frac{\phi_i^p \mathbf{C}_{ij}}{\phi_j^s}, \quad \phi_j^s = \sum_{i=1}^{m} \phi_i^p \mathbf{C}_{ij} \qquad (2)$$

where Φ_j^s is the j-th STC frequency, Φ_i^p is the i-th PDS frequency, and C_{ij} is the j-th conditional probability to i-th PDS.

With a similar approach, twelve types of importance analyses can be performed: initiators to PDS, SET sequences to PDS, SET sequences to STC, initiators to STC, PDS to STC, CPET sequences to STC, sequence types considered to given top events, and each sequence to total frequency for given five types of event tree. All the results can then be displayed graphically in the form of Pie graph or Bar chart. If needed, they can also be printed in the form of table.

On the other hand, the sensitivity analysis is taken by two levels. One is the intermediate level sensitivity analysis which investigates the variation of intermediate results due to the change of initiator, SET, and PDS events. This type of sensitivity is analyzed by the matrix formula like the importance analysis. Three types of sensitivity analyses can be performed in this module: initiators to PDS, initiators to STC, and PDS to STC. Then all the results can be displayed in the form of sensitivity table. For example, the sensitivity of i-th PDS to j-th STC can be evaluated by

$$\mathrm{Sen}(\phi_j^s : \phi_i^p) = \frac{\Delta\phi_j^s}{\Delta\phi_i^p} \qquad (3)$$

where $\Delta\Phi_i^p$ is change in the i-th PDS frequency and $\Delta\Phi_j^s$ is the resultant change in the j-th STC frequency.

The other level characterized by CONPAS is the basic event level sensitivity analysis which identifies the variation in the probability estimates on the overall results for each phenomenological event in DETs. This type of sensitivity analysis is performed by utilizing the scheme for uncertainty analysis to simultaneously manipulate a set of sensitivity cases rather than a tedious one-at-a-time approach with one-by-one selection of sensitivity cases. By this approach, the basic event level of sensitivity analysis can be incorporated into a realm of uncertainty analysis.

2.2.3. Uncertainty Quantification

Accident progression addressed in Level 2 PSA is uniquely determined by the prior conditions and thus if the same conditions are given, the resultant accident progression is always fixed into one. Problem is that a limited knowledge or understanding about the prior conditions gives rise to different accident progression possibilities. This type of uncertainty is characterized by phenomenological uncertainty which is scaled by the subjective probability expressing expert's degree of belief on given phenomena [3]. Thus, uncertainty analysis is required to compensate poor understanding of accident progression models and incompleteness of numerical input data. The principal approach for uncertainty analysis adopted by CONPAS is to utilize a Latin Hypercube Sampling (LHS) or a Monte Carlo Method optionally, with incorporating the appropriate correlation coefficients into a sampling scheme. In the sampling process, the correlation coefficient is currently utilized by rank of sampled inputs and only two cases are considered like NUREG-1150 approach [3]; independent case (i.e., rank correlation coefficient is zero) and perfectly dependent case (i.e., rank correlation coefficient is greater than 0.99). Major inputs characterized by the correlation coefficient are binary branches and containment loading pressures.

As given in Table 4, four types of uncertainty inputs can be utilized in CONPAS: Type 1 and Type 2 characterized by phenomenological uncertainties (subjective probability), Type 3 characterized by expert's opinion (variation in the subjective probability estimate), and Type 4 characterized by containment loading and capacity (parameter distributions). Type 1 and Type 2 are utilized to investigate the impact of uncertainty on the deterministic accident phenomenologies and the related subjective probabilities can be normally obtained by the overlap of probability distributions on the occurrence criteria and parameter values controlling the accident phenomenology or by the expert judgment. Type 3 is available in investigating the impact of expert-to-expert variations in the subjective probability estimates on the overall results for each phenomenological event and the approach is analogous to assuming what other experts might select in the process of subjective probability estimation. Type 4 is utilized to estimate the containment failure probabilities, which is made by combining the capacity distributions subjected to each failure mode and the loading pressure distributions given as prior conditions. As summarized in Table 2, several types of probability distributions are currently available associated with Type 4, i.e., (log) uniform, (log) normal, and empirical distribution. As the results of statistical propagation of these uncertainty inputs, the CPET endpoint probabilities of required number are generated for each PDS and they are then integrated to obtain the probability distributions for each sequence of STC considered.

All uncertainty inputs are assigned to the DET basic events, which are prepared in the form of uncertainty input deck. Table 5 shows a typical type of uncertainty input decks which can be utilized by CONPAS, with line by line comments for each component. The former part of Table 5 specifies title, sample size, consideration of correlation between inputs, and type of containment failure modes. The latter part specifies uncertain branch set, their distribution types, uncertain data type and distribution, and final correlation coefficients used. In particular, naming convention is used to specify a given branch set. For an example, a code name D1Q2C2 is used to specify branch set corresponding to the second dependency case of event heading 2, in DET # 1. The remaining informations are described in the comments of the input deck.

2.2.4. Calculation of Containment Failure Probability

Containment failure timing and modes have been considered as one of key stages in severe accident progression analysis. Depending on its impacts on severe accident progressions, containment failure time frame is roughly categorized into an early containment failure, a late containment failure, and no containment failure. If containment failure

Table 4. Uncertainty Input Types Applicable to Uncertainty Analysis

Uncertainty Input Types	Branch Types	Distribution Types
Type 1	Specified branch probabilities (only binary branches)	Cumulative distribution (discrete case) Probability density function (continuous case)
Type 2	Specified branch index (multi-branches)	Discrete probability distribution
Type 3	Specified branch probabilities (multi-branches)	Discrete probability distribution (weighting factor)
Type 4	Specified parameter values Specified failure modes	Containment loading distributin Containment capacity distribution

Table 5. Sample Uncertainty Input Deck

Title	Sample Uncertainty Input			*: title*
NOBS	100			*: sample size is 100*
NVAR	5			*: 5 branches are considered*
Corr	YES			*: correlation is used*
CFMode	2			*: 2 failure modes are considered*
UserDistribution	D1Q2C2			*: Type 2 uncertainty, branch set*
2	3			
1	0.5			
2	0.3			
3	0.2			
UserDistribution	D2Q3C1			*: Type 1 uncertainty, branch probability*
1	2			
0.3	0.4			
0.7	1.0			
LogNormal	D3Q2C1			*: Type 4 uncertainty, loading pressure*
1	1			
70	1.2			
UserDistribution	D4Q3C4			: Type 3 uncertainty, experts' opinion
3	4			
3				
0.1	0.2	0.7	0.2	
0.3	0.3	0.4	0.2	
0.2	0.7	0.1	0.4	
0.5	0.3	0.2	0.2	
Correlation Matrix				*: correlation between related inputs*
3				
1	2	0.999		
2	3	0.999		
3	4	0.999		
Failure Mode & Distribution				
LogNormal	Leak			*: capacity distribution for leak*
140.0	1.30			
UserDistribution	Rupture			*: capacity distribution for rupture*
5				
120	0.1			
140	0.3			
160	0.5			
180	0.7			
200	1.0			

does occur, for each case, it can be by a small leak failure or by a large rupture failure. As the natural result, the source terms will be quite different for each of these combinations. Also, the containment failure modes and related probabilities are somewhat differently affected by the pressurization rate of containment, i.e., fast pressurization and slow pressurization. For fast pressurization, a leak does not arrest pressure rise in the containment and increasing possibility exists that the containment may fail at a higher pressure by a rupture. This means that a larger size of failure (i.e., rupture) can follow a smaller size of failure (i.e., leak) but no vice versa. For slow pressurization, the containment is assumed to fail by whichever failure mode occurs at the lowest pressure. In this context, slow and fast rates refer to the rate of the pressure rise relative to the leak rate, not with regard to the containment structural response. For a detailed analysis of accident progression, CONPAS utilizes both types of pressurization processes for containment failure probability evaluation [20]. In addition, CONPAS employs an alternative approach that the containment failure probability for each mode is independent of the pressurization rate and the final failure mode is considered as a rupture type when a leak and a rupture occur simultaneously [21]. That is, a leak only failure probability is given by a leak probability except a probability transferring from the leak to the rupture type, and a rupture type failure probability is given as only the given rupture probability itself. For given containment peak pressure, in this case, the probability for i-th failure mode, $p(m_i \mid \tau)$, is expressed by

$$p(m_i|\tau) = \int_0^{\tau} f_i(\tau')\prod_{j>i}[1-F_j(\tau')]\,d\tau' \quad (4)$$

$$p_{no}(\tau) = 1 - \sum_{i=1} p(m_i|\tau) \quad (5)$$

where $p_{no}(\tau)$= probability of no failure, and $f_i(\tau)$, $F_i(\tau)$ = probability density function and cumulative distribution of containment capacity for i-th failure mode, respectively.

The containment failure probability obtained by Eq.(4) is in between a failure probability due to slow pressurization (optimistic) and a failure probability due to fast pressurization (pessimistic) of NUREG-1150. Under the existence of uncertainty in pressure, at any cases, the mean estimate of i-th containment failure probability $\hat{p}(m_i)$ is given by

$$\hat{p}(m_i) = \int_0^{\infty} f_L(\tau)p(m_i|\tau)d\tau \quad (6)$$

where $f_L(\tau)$ = probability density function for containment load.

In the case of point estimate, these peak pressures can be directly utilized in the form of parameters in DETs rather than probabilities. In this case, CONPAS evaluates automatically the resultant containment failure probability for a leak failure mode and/or a rupture failure mode. For the evaluation of containment failure probability, five containment capacity distributions were currently hard-wired in CONPAS : uniform, loguniform, normal, lognormal, and empirical distribution. For uncertainty analysis, however, they should be manipulated in the input deck. As the result, peak loading pressure distributions and capacity distributions are combined to generate a specified number of failure probabilities.

2.3. CONPAS Auxiliary Modules

Event Tree Converter Module: By the module, several types of event trees prepared by other PSA codes can be converted into the CONPAS specific event trees. Major advantages of the module is to utilize easily results of other PSA codes without tedious efforts.

Mechanistic Code Plotter Module: The CPETs are normally based on time sequences: before core melt, in-vessel core melt progression, ex-vessel progression after RCS boundary failure, and core debris deposition and coolability. In order to determine such timing and physical behavior for the accident progression including the source term for each important PDS, most Level 2 PSA utilizes a phenomenological code as well as expert's judgments whose results are reflected in CPET branch input. The Mechanistic Code Plotter Module utilizes the results of accident progression analysis based on the phenomenological codes. It is to extract the control variables from accident scenarios and to summarize the ranges of severe accident issues. For the purpose, the module has three options: (a) individual plot for each control variable, (b) merged plot for several control variables, and (c) merged plot for several different scenarios.

Text Editor Module: Many PSA applications require a diverse presentation of the results. Tools could be developed to automate PSA output and simplify the level of effort required to generate results. While CONPAS Computation Module utilizes a function for plotting the results of uncertainty and importance analysis for those purpose, Text Editor module is used to report the results and to prepare the uncertainty input deck without any help from commercialized editors.

3. Implementation Test

In order to verify the performance of CONPAS in real systems, the present code has been applied to a preliminary Level 2 PSA for the internal events of Ulchin 3&4 units (UCN 3&4) which is being performed as one of individual plant examinations (IPE) in Korea. The UCN 3&4 units are two loop, Korea Standardized Nuclear Power Plants (KSNP) pressurized water reactor of 2815 MWth with a large dry containment. The fundamental approach used to perform the Level 2 PSA is the same as the above example application and the computational procedures are as follows [21]:

(1) Twenty three Level 1 event trees have been extended to include the status of containment safeguards of UCN 3&4 into SETs of this code system and each individual sequence has been quantified by linking together the fault trees for the UCN 3&4 system failures that lead to a given sequence of events.
(2) Nine PDS parameters have been selected to define PDSs and they are containment bypass, containment isolation, type of accidents like SBO and LOCA, power recovery, in-vessel injection, containment recirculation cooling, containment fan cooling, RCS pressure during core damage, and cavity condition. Based on the PDS parameters, a general PDS logic diagram with forty five endpoints has been constructed and each PDS endpoint represents a unique accident progression starting point with respect to the CPET. Then the quantified results of SETs have been propagated through the PDS logic diagram to obtain the frequencies of the PDSs.
(3) A general CPET and several accident specific CPETs have been developed to model the UCN 3&4 containment responses during severe accident progressions. To simplify the structures of a general CPET, the number of top events in the CPET is reduced to nine and they are mode of induced primary system failure, core melt arrest, alpha mode containment failure, amount of corium ejected out of cavity, no early containment failure, no late spray failure, debris cooled ex-vessel, mode of late containment failure, and basemat melt-through. The number of general CPET endpoints is ninety five. Events that contribute to these top events and/or aid in the assessment of the branch probabilities are relegated to the corresponding DETs. Then all CPETs corresponding to the PDSs have been quantified by combining the quantified PDSs and DETs.
(4) The final step of the analysis is to quantify STCs. Eight STC parameters have been

selected to analyze the source term release characteristics and they are containment bypass, containment isolation, core melt progression stopped before RV failure, no alpha mode containment failure, time of containment failure, mode of containment failure, debris cooled ex-vessel, and no recirculation sprays failure. All combinations of possible values for each of the STC parameters generated nineteen source term categories. Finally, the constructed STC logic diagram has been quantified by combining the CPETs and PDS under the STC event classification rules.

As a preliminary result of the Level 2 PSA for UCN 3&4 internal events, Table 6 provides the conditional probabilities for each containment failure mode. As shown in Table 6, the total value of containment failure probabilities conditional on the internal core damage has been estimated to be 0.251. The most dominant contributor to containment failure mode was the containment bypass (14.4 %). The second contributor is late containment failure (8.2 %). The probability for a basemat melt-through is determined to be 1.9 %. The remaining results compared with the other PWR plants are also shown in Table 6.

As a way to compare with a verified code for Level 2 PSA, the above procedure has been applied to a commerical computer code for Level 2 PSA with the same accident progression logic, NUCAP+, step by step. The result has shown that over all procedures for accident progression analysis, CONPAS produces the identical numerical values to those of NUCAP+, with similar speed of code run. This is a reason why the comparative results between the two codes are not given in this paper.

In order to study a feasibility for CONPAS specific uncertainty analysis, on the other hand, a type of uncertainty quantification for UCN 3&4 Level 2 PSA has been made through 1000 LHS samples for important DET branch parameters and the results are given in Table 7. As shown in Table 7, mean values for each containment failure probability approach to their point estimate

Table 6. Comparison of UCN 3&4 with Other PWR Plants:Conditional Probabilities of Containment Failure for Internal Initiating Events

Plants CF Types	UCN 3&4(a)	YGN 3&4	Palo Verde	Surry (IPE)	Surry(b)	Zion(b)
No CF	0.749	0.782	0.72	0.535	0.81	0.730
ECF	0.006	0.007	0.1	0.006	0.01	0.014
LCF	0.082	0.063	0.08	0.253	-	0.240(c)
BMT	0.019	0.044	0.06	0.039	0.06	-
BYPASS	0.144	0.104	0.04	0.167	0.12	0.006

Note : (a) : Preliminary Results for UCN 3&4
(b) : NUREG-1150
(c) : LCF includes that of basemat meltthrough.
No CF = No Containment Failure
ECF = Early Containment Failure
LCF = Late Containment Failure
BMT = Basemat meltthrough
BYPASS = Containment Bypass

Table 7. Results of Uncertainty Analysis for UCN 3&4 Accident Progression: Conditional Probabilities of Containment Failure for Internal Initiating Events

CF Types	min	5%	median	95 %	max	mean
No CF	0.357	0.625	0.763	0.814	0.821	0.738
ECF	0.001	0.001	0.002	0.008	0.423	0.007
LCF	0.016	0.042	0.088	0.094	0.102	0.084
BMT	0.000	0.000	0.005	0.115	0.295	0.028
BYPASS	0.138	0.138	0.138	0.138	0.396	0.144

values.

4. Concluding Remarks

A PC window-based computer code, CONPAS has been developed to perform an integrated Level 2 PSA and to improve major two weaknesses of the existing codes for Level 2 PSA: (a) While availability of the existing codes is very limited under the Windows environment, the present code is operated in the environment of MS Windows. (b) While the existing codes except for EVNTRE code do not provide a capability for Level 2 PSA specific uncertainty quantification, the present code quantifies the uncertainties systematically.

In this paper, first, the key features of CONPAS and its computational logic for accident progression analysis have been mainly described. And then, its computational performance has been assessed through an application to a full scope Level 2 PSA of a real plant. As a result of feasibility study, the numerical outcomes for point estimate have been verified by an existing Level 2 PSA code, with similar speed of code run. In addition, a result of uncertainty quantification shows reasonable uncertainty bands under a logical consistency with the point estimate. These apparently indicate that CONPAS can be well applied to the real PSA. Based on these results, the following conclusions are drawn:

- CONPAS is a verified code for integrated Level 2 PSA employing a logically consistent accident progression approach characterized by two types of supporting trees (e.g. SETs and DETs). By the logic, it is possible to describe effectively the accident progressions with pertinent number of events on the CPET and as the result, it is possible to trace out visually each accident pathway.
- CONPAS provides several computational features including systematic uncertainty, importance, and sensitivity analysis for many phenomenological events which are expected in every stage of accident progression, which are essential features in performing Level 2 PSA.
- CONPAS provides the highly improved user-friendly interface compared with the existing Level 2 PSA codes, including convenient edition of event trees through mouse-driven and colored graphics, systematic data operation, and automatic check of unreasonable inputs.
- CONPAS provides several functions for reporting, including colored plots, graph, and tabling of final outcomes. Also, it provides two additional features: data analyzer for analysis of severe accident code results and text editor for refined reporting of the computed results.

As an on-going work, ST analyzer module is being currently developed and in near future the product will be incorporated into the CONPAS. Its main purpose is to assess source terms of a more complete range of accident scenarios including uncertainty analysis, which utilizes a data base obtained through parametric calculations. After completing this additional work, the CONPAS code will have more extended capability for Level 2 PSA.

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