Passive system Evaluation by using integral thermal-hydraulic test facility in passive NPP(nuclear power plant) PSA(probabilistic safety assessment) process

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Abstract: Passive safety engineered systems are designed to take effect by physical phenomena or passive procedure during the scenario of imaginary accident of AP600/AP1000/CAP1400 passive safety type nuclear power plant.

Generally, associative thermal-hydraulic experiments have been studied to support specific physical phenomenon research or evaluation model development in these scenarios.

Data from T-H experiment is credibility and direct. However, for the size of safety engineered systems of NPP are very huge, it's almost impractical to simulate a whole physical process by original scale test facilities. Some reduction scaled test facilities have been applied in design verification or safety research.

So, it's worthy to explore how to apply the research of scaled integral T-H experiment target at the specific physical process or phenomena in PSA procedure.

Scaling analysis method is usually applied in the integral test facility design, construction, and data evaluation especially. Through the scaling analysis and evaluation of experiment data, the uncertainty of every test result can be achieved. The result, trend or uncertainty of specific parameters of physical phenomena or process can be explicated. If test facilities and experiments are implemented by scaling analysis appropriate, the most important result of test can present the prototype one in some degree (some uncertainty level). By these, the test can present the target physical phenomena simulated. And the prototype passive system can be explored by experiment result in some uncertainty degree level.

Containment Experiment via integral safety validation test facility (CERT) has been set up for design validation of passive containment cooling system(PCCS) of CAP1400 NPP. CERT can simulate LOCA or MSLB accident scenario by equal ratio power-volume. The figure of merit of CERT is the pressure inner containment. Different trends of figure of merit can be obtained by adjust the boundary or initial condition of experiment, such as total enthalpy of steam injection, flow rate/coverage of cooling water outer of containment, wind speed in the annulus(the structure between shield and steel containment), concentration of non-condensation gas(the helium which is used to simulate hydrogen during accident), and so on. Besides, it's also can be achieved which quantitatively defines the possibility of the figure of merit beyond the design criterion. According to the scaling analysis and the experiment results(by integral test facility) of corresponding important physical phenomena, the quantitative performance assessment of PCCS can be obtained. Afterwards, these evaluation can support II level PSA of passive safety NPP.

Keywords: Passive, PSA, Scaling Analysis, AP1000, CAP1400, CERT.

1. Research of Engineered Safety System in Large Passive Plant

Recently, passive systems applied in nuclear power plant became more and more widespread. In AP1000/CAP1400 type NPP, most of the engineered safety systems are designed by physical process functional characters without any power of electric or active mechanics. It's a necessary issue to evaluate these systems in a way of PSA method. The safety analysis of related physical processes or phenomena are usually the start of begin.

Although there are lots of works in PSA quantification, it's difficult to apply traditional PSA methods in evaluation of passive system. How to get the correct value which expresses the specific performance of the physical procedure must be the one of most difficulties.

In the guide of NUREG-5809 and relative materials, some separate and integral thermal-hydraulic test facilities have been set up the aiming to the technically researching of physical phenomena expecting in the passive system action during accident scenarios. It's valuable to develop an approach to achieve

the performance of prototype system by converting test results, in order to support PSA applied in passive system safety evaluations.

By deducing the data from thermal-hydraulic experiments, the physical performance quantification will be more reliable, and can be confirmed and validated in PSA processes.

2. T-H test method

The first passive safety characteristic nuclear power plant AP1000 has been constructed in China. Similar to AP1000, State Nuclear Power Technology Corporation (SNPTC) of China has designed CAP1400 to enhance the plant power and the ability of relative engineered safety system. Because of the lack of experiences and uncertainty in increasing plant power, a serial safety issues have been researched, especially the passive reactor core cooling system (PXS), passive containment cooling system (PCCS), and in-vessel retention (IVR). Focus to these issues, relative separate or integral experiments have been taking effect.

These experiments draw on the experiences of previous researches especially during the development of AP600/1000 design. Applying the spirits of scaling analysis and uncertainty methods, some innovations have been carried out in the experiments researches according to CAP1400 features.

2.1. Severe accident research and analysis

Paper [1] and [2] have set up a frame solution procedure of NPP severe accident safety issues. Zuber et. al., had developed the Integrated Structure for Technical Issue Resolution (ISTIR) in 1990's. Severe Accident Scaling Methodology (SASM) is one of the elements.

In ISTIR, there are 5 main elements combined the whole structure, specify the safety issue and important phenomena, scaling methodology and experiments, technical resolution by experiment and uncertainty quantification, analysis (and uncertainty quantified) by frozen code, and code development. In these 5 steps, specifying the critical physical phenomena will be the first and most important one. By achieved the phenomena identification and ranking table (PIRT), the relative experiment (separate or integral), analysis, code development can be set up and directed in process of SASM.

SASM can be regarded as the guide for thermal-hydraulic experiment research. There are some details. Three elements compose SASM by [1]:
1. Experimental requirements.
   According to the PIRT, the experimental objectives can be specified in this step.
2. Evaluation and specification for experiments and testing.
   In this step, scaling analyses should be applied. Similarity criteria should be set up. Separate or Integral experiment facility (experiments) should be specified. Relative models, correlations, facilities distortions, test design optimizing should be developed.
3. Data acquisition and documentation.
   By experiment operation, data can be achieved in different conditions. Data base and uncertainties by quantification can be established.
   With the whole procedure, facilities design requirements & specifications, test results, and experiment data etc., can be documented in this step.

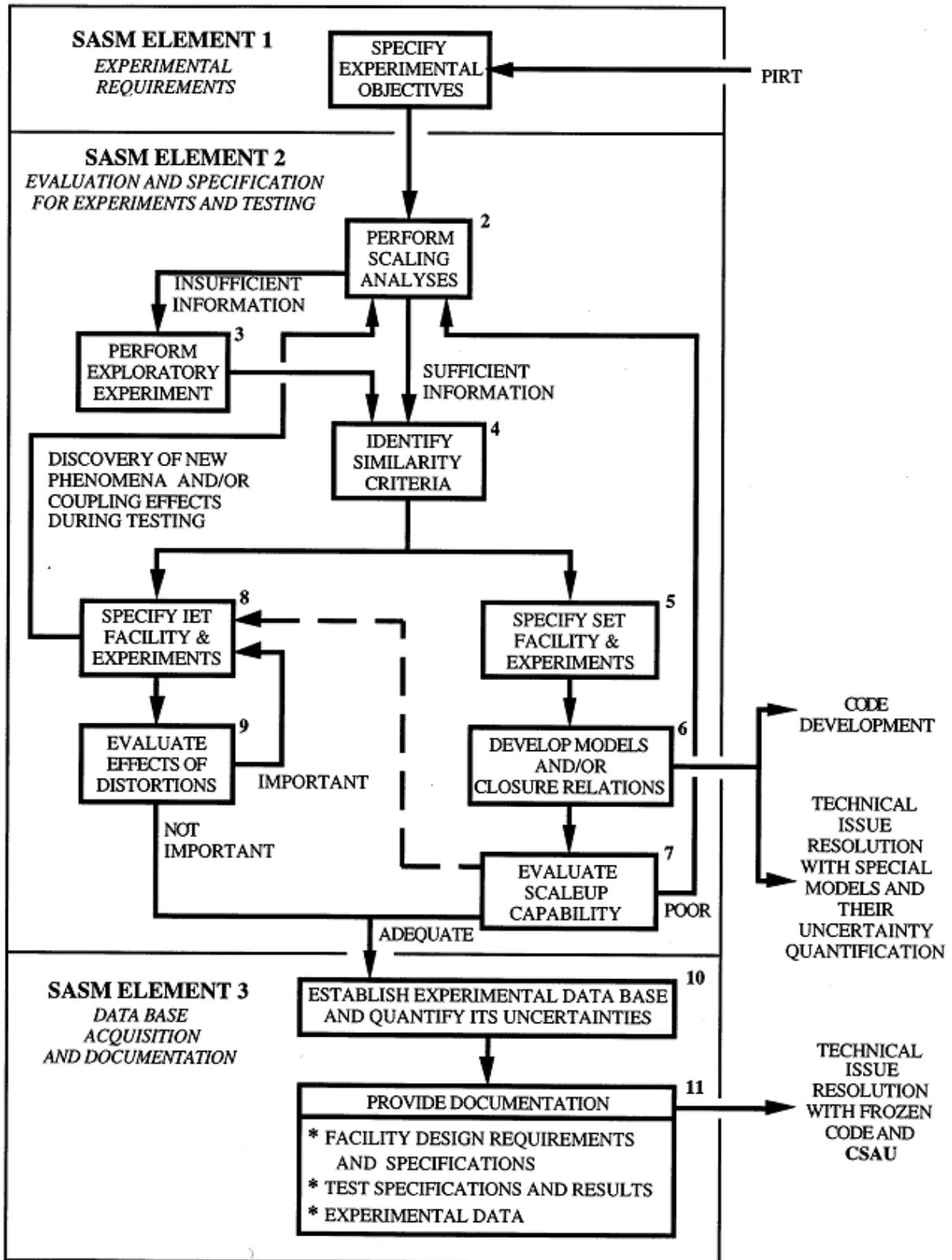The main frame of flow diagram of SASM is showed in [1] as Fig.1:

Fig.1 Flow diagram for SASM [1].
The details of the flow diagram will not be discussed here, see [1].

2.2. Scaling analysis methodology application

According to SASM execution process, there are several critical steps in the process of scaling analysis during thermal-hydraulic experiments design.

1. To specify PIRT according to the scenarios of the specific NPP by expert judgment.
2. To identify the critical physical processes or phenomena, and gather the conservation equations and relative correlations.
3. To deconstruct the system by subsystems and physical fields etc. by H2TS (hierarchical, two-tiered scaling) procedure.
4. To define the sub-scaled facilities and boundary conditions especially the characteristic dimensions.
5. To explicit the requirement of abilities and precisions of measurement and control system by feedback of application of scaling analyses or H2TS methods.

The flow diagram of scaling analysis method namely `H2TS' (hierarchical two-tiered scaling analysis) of SASM is showed in [1] as Fig.2:
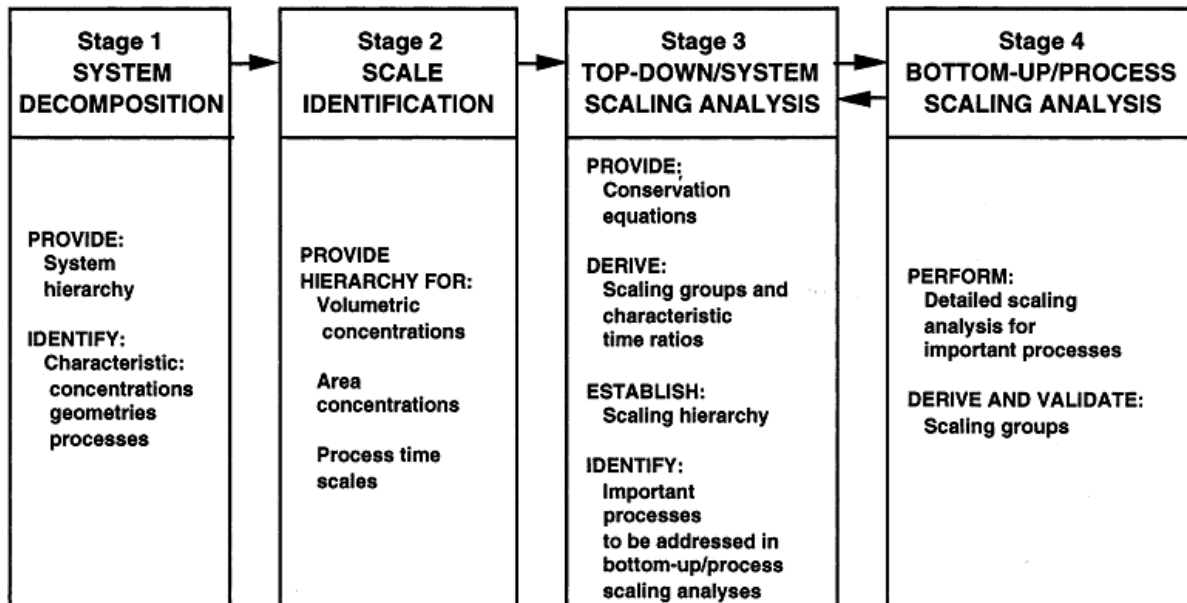

Fig.2 Flow diagram for H2TS [1].

2.3. Objectives of sub-scaled tests facilities

Reactor core cooling and containment integrity are the most two important safety issues in nuclear power plant design or safety research. For CAP1400, two integral experiment facilities have been constructed to the PXS (passive core cooling system) and PCCS (passive containment cooling system, also PCS) separately.
ACME (Advanced Core-Cooling Mechanism Experiment) simulates the situations of core covered by coolant in the act of PXS, during whole range of pressure in LOCA (Loss Of Coolant Accident) or SBLOCA (Small Break Loss Of Coolant Accident) accident scenarios.
The missions of ACME are:
- To simulate the operation of passive core cooling system of CAP1400 for SB-LOCA.
- To validate the engineering design of the passive core cooling system.
- To collect thermal-hydraulic data for safety code assessment.

CERT (Containment safety vErification via integRal Test) simulates the trend of containment inner pressure and energy transferred in act of PCCS. During steam mass & energy injection, the power to the test vessel volume is equal to the ratio of prototype during the accident scenarios.
The missions of CERT are:
- To validate the applicability of WGOTHIC(safety code for containment assessment)
- To verify the engineering design of the passive containment cooling system
- To scaled-simulate the physical process in accident scenario, and the performance of passive containment cooling system of CAP1400

These two integral test facilities are all under operation this time in SNPTRD (State Nuclear Power Technology Research & Development center). Some instruments are under adjustment in early 2014. The experiment which is simulating LOCA scenario of CAP1400 will be executed in the mid of the year.

3. CERT introduction

The test facility named `CERT' is the abbreviation of "Containment safety verification via integral test". As mentioned above, the main purpose of CERT is to verify the PCCS ability in specific accident scenarios by sub-scaled model.

CERT test section is a bearing pressure steel vessel which length (include diameter) ratio (test to prototype) is 1:8. Apart from the test vessel, several dynamic or accessory system consist CERT, as below [3]:
- Steam supply sys.
- Coolant supply sys.
- Air compressor/vacuum sys.
- Non-condensable gas supply sys.
- Measure sys. (Common measure, Digital CCD, LDV[i], etc.)
- Control sys. (PLC)
- Database.
- Other auxiliary instruments.

By the PCCS design of CAP1400, the related components and installations of PCCS are all sub-scaled according to the length ratio. The operation parameters or ability of the systems are also designed to keep consistent with the requirements of the parameters after sub-scaled corresponding to the prototype characteristic parameters. Some important items list below:
- Scale: 1:8 (model to prototype)
- Height: 9.125 m
- Diameter: 5.375 m
- Design pressure: 0.7 MPa(a)
- Design temperature: $< 200℃$
- Shell thickness: 18.0~20.0 mm
- Total height: ~15 m
- Steam mass rate: 1.5 t/h~108.0 t/h (four branches supply)
- Coolant mass flow rate (outer containment): 0~8.0 t/h

The key character of CERT is the performance of mass & energy release, in other words, the ability of steam supply system (SSS) operation. So the most important accessory system is the steam supply system. By considering the ratio of power to volume / area, SSS can simulate the LOCA and MSLB scenarios in a desirable state. By the synthetic action of other systems, the conditions of boundary can be achieved, such as inner containment temperature, pressure, gas flow rate, humidity, non-condensable component, outer containment water film flow rate, wind velocity in annulus, etc.

4. Process of test result apply to PSA evaluation

The figure of merit in CERT experiment is ***the pressure inner containment***. The main target of experiment is to achieve the pressure trend in the specified boundary and initial conditions. Futhermore, the inner pressure of prototype NPP can be inversely deduced by scaling analysis methodology with a sort of uncertainty of course.

Here we assign the inner pressure is the criterion of containment failure. Namely, if the inner pressure is greater than a specific constant value P_{crit} the containment is assumed to failure.

In fact, the peak pressure will be achieved in every test, however it's a little different even given the nearly same conditions (since attaining the exactly same conditions in an integral T-H experiment is very hard, little bias that do not affect results can be accepted. However this conclusion should be confirmed by sensitive analysis,). Because every parameter has a specific distribution, the inner

pressure which is the function of these parameters also has a distribution. And this distribution or uncertainty range can be seemed as the uncertainty propagation of relative parameters'.

The data of LOCA or MSLB scenario experiments is used to evaluate the failure of containment.

As the peak pressure values from all previous tests can be treated as the space of containment performance sampling. The sample of failure occurred because of inner pressure over the criterion.

During this process, the pressure value is fluctuated in a range, because of the other relative parameter's variation as mentioned above. By majority times of repeat tests, the probability distribution of the peak pressure value can be concluded by a number of results. And the probability of containment failure can be deemed as the probability integrated by counting the value greater than the criterion.

The expression of inner containment is deduced from energy conservation equation. The pressure is the integration

$$\pi_{p,\tau} XV \frac{dP}{dt} = \dot{m}_{brk}(h_{brk} - h_{stm}) - \sum_{i=1}^{N}(\Lambda(\pi_{P,cond,i}\dot{m}_{stm,i}) + (\pi_{P,q,i}h_{q,i}A_i \, \Delta T_{if,i}))$$

(1)

here P : containment (or test model) inner pressure value,

t : time,

$\pi_{p,\tau}$: dimensionless value represent the pressure development of time because of mass/energy injection. $\pi_{p,\tau} = X \frac{p}{\rho_{g,brk}}$, while $\rho_{g,brk}$ is the density of steam blowing from the nozzle (to simulate breach). While X is the coefficient of atmosphere existence in the containment..

Λ : the pressure develop because of the mass increasing, $\Lambda = \frac{C_p P_{stm}}{ZR\rho_{stm}}$, while C_p is heat capacity at constant pressure, Z is compressible factor, R is gas constant, ρ_{stm} is density of steam in containment, P_{stm} is partial pressure of steam in containment.

$\pi_{P,cond,i}$: dimensionless value represent the pressure development affected with the condensation on the i th component inner containment.

$\dot{m}_{stm,i}$: mass flow rate of the condensation on the surface of the i th component inner containment.

$\pi_{P,q,i}$: dimensionless value represent the pressure development affected with the radiation and convection on the surface of i th component inner containment.

$h_{q,i}$: the equivalent heat transfer coefficient of radiation or convection heat transfer mechanism on i th component surface.

A_i : the equivalent area of heat transfer by radiation or convection.

$\Delta T_{if,i}$: the equivalent different of temperature of the atmosphere to the film on the i th component surface.

V : the freevolume of containment or containment model (test model/section).

Some parameters above are the function of other more particular variables, such as $\pi_{p,\tau}$ or Λ mentioned above.

So the pressure equation can be written as:

$$p(t, x_i) = \int_0^t f(x_i)$$

(2)

$f(x_i)$ is the function of x_i , while x_i represents the i th parameter of relative measurement variables.

The peak pressure appeared in one test can be expressed as:

$$p_{max} = max[p(t, x_i)]$$

(3)

By the equations and definitions above, the failure probability of the PCCS can be indicated as the probability of the event indicating that PCCS cannot reduce inner pressure lower than the criterion value during the DBA accidents.

$$P[\text{fail of PCCS}] = Prob[p_{max} > p_{crit}]$$

(4)

While *P[X]* is the probability of random event *X*. p_{crit} is the criterion of containment (const value).

The uncertainty evaluation of "p(t)" will be deduced from scaling analysis by dimensionless equations and propagation of parameter bias, and by dealing with data from test results.

The main flow of evaluation process lists below. Because of CERT tests haven't finished yet, the real values haven't been substituted.

1. To establish the quantitative relationships between the test model and prototype PCCS of NPP, by using conservation equations and dimensionless correlations.

   The most important one is the energy equation in the form of pressure (equation 1). The dimensionless process can be applied to this equation. After dimensionless process, the equation can be simplified as:

$$\left(\frac{dP}{dt}\right)_p$$

$$= \frac{\left(\pi_{p,\tau}XV\frac{dP}{dt}\right)_T}{\left(\pi_{p,\tau}XV\right)_p} - \frac{\left(\left(\Lambda\sum_{i=1}^{N}(\pi_{P,cond,i}\dot{m}_{stm,i})\right)_P - \left(\Lambda\sum_{i=1}^{N}(\pi_{P,cond,i}\dot{m}_{stm,i})\right)_T\right)}{(\pi_{p,\tau}XV)_P}$$

$$- \frac{\left(\left(\sum_{i=1}^{N}(\pi_{P,q,i}h_{q,i}A_i\ \Delta T_{if,i})\right)_P - \left(\sum_{i=1}^{N}(\pi_{P,q,i}h_{q,i}A_i\ \Delta T_{if,i})\right)_T\right)}{(\pi_{p,\tau}XV)_P}$$

(5)

   Here, $(...)_P$: the relative parameter values of prototype system.
   $(...)_T$: the relative parameter valures of test model.

   The relative correlations can be used to close the equation above. such as:

$$h_{q,i} = 0.13\ \frac{k}{\left(\nu^2/g\right)^{1/3}}\left(\frac{\Delta\rho}{\rho}\right)^{1/3}Pr^{1/3}$$

   and etc (didn't describe them all).

   And much more parameters as $\dot{m}_{stm,i}$ or $\pi_{p,\tau}$ ..., are all can be deduced from lots of basis measured variables, such as the specific local temperature\pressure and so on.

2. To quantify the value of inner pressure and its uncertainty/ distribution etc.

   The most parameter values of $(...)_T$ in the equation can be obtained from test, while others can be predicted by T-H correlations, or general database. Then the value of pressure can be deduced by given the parameters' value above.

   Here, π_T or π_P means a specific physical process/mechanism corresponding to the test (T) or prototype (P). And $\frac{\pi_T}{\pi_P}$ indicates the ratio of relative parameter belongs to test and to prototype.

   According to the spirit of scaling analysis, the nearly $\frac{\pi_T}{\pi_P}$ approaches to 1, the similarly of the physical phenomena in the test facility to the one in the prototype system.

   In fact, it's impossible to keep everyπ in the dimensionless equations to 1. If a deviation appeared, it means the corresponding physical phenomena or process is not exactly the same. Then PIRT can be used to determine whether the phenomenon (π represents) is important to the figure of merit or not. However, it's difficult to quantify the influence of Π deviation to the result，because PIRT has just been identified in high/mid/low ranks by expert judgments.

3. To obtain the figure of merit (the pressure value) and the failure probability with a specific uncertainty of prototype PCCS. The pressure value can be expressed as the integration of equation (5).

   The uncertainty of the peak pressure value can be expressed as:

$$\Delta p_{max} = \Delta p(t)|_{t=t_{pmax}} = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial p(t,x_i)}{\partial x_i} * \Delta x_i\right)^2}\ |_{t=t_{pmax}}$$

(6)

The partial differential expression in the right of the equation seems very difficult to calculate (because the expression of $p(t, x_i)$ is very complex). However the numerical method can be applied in the calculation. In fact the important of variables can be achieved by test (most of x_i or Δx_i), then others can be digested from general database or expert judgments. And there exists uncertainties of general database & experts judgments too, which is not considered here.

5. Conclusion

To sum up, in CAP1400 NPP safety verification experiment, the process of applying the thermal-hydraulic integral test result to evaluate the system failure probability. And the method of sub-scaling analysis experiment design has been introduced.

CAP1400 PCCS test facility CERT has taken nearly 4 years from design to bring into service. During the design period scaling analysis and relative key methodologies were draw from ISTIR and SASM. Some tricks were deeply revised or modified in order to consist with physical process anticipated in the containment. The measurement and control devices all have calibrated and adjusted to achieve a high degree of accuracy. High quality & reliability test data have been obtained unfailing nowadays.

The main steps of the process to evaluate the PCCS fail probability which can be applied to the PSA assessment further, by scaled T-H experiment is summarized below:

1. To digest the key physical phenomena or transport processes from PIRT of target NPP (CAP1400).
2. To use H2TS method to set up the frame of the analysis of these important physical processes considered, top to down combined with bottom up (conservation equations and specific correlations).
3. To establish the quantitative connection between the test model (1:8 scaled) and the prototype PCCS of CAP1400 NPP, by scaling analysis -- dimensionless equations.
4. To evaluate the value and the uncertainty or distortion of test result for each parameter. From which the relative parameter value and uncertainty of prototype system of NPP can be deduced (also dimensionless correlations should be used).
5. To obtain the distribution of specific key parameters by repeating experiments for times. Then the distribution or characteristic value can be achieved through the quantitative connections with some kind of uncertainties.

From above basis, a further uncertainty analysis to test results is necessary to proceed. In order to make an integrated similarity or distortions about the test and prototype. And the test result of the T-H tests can be evaluated quantitatively, completely, reliably to predict the performance of prototype engineered safety system in some confidence level.

For PCCS of CAP1400, the result of the test data can be applied in the assessment of II level PSA.

References

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[i] LDV: Laser Doppler Velocimetry (LDV) measurement.