Identification of Important Phenomena under Sodium Fire Accidents Based on PIRT Process

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Abstract. JAEA has developed sodium fire analysis codes SPHINCS and AQUA-SF for numerical evaluation of the consequence of a sodium fire accident, which is one of key issues in sodium-cooled fast reactor (SFR) plant. This paper describes a PIRT (Phenomena Identification and Ranking Table) process for a sodium fire event. The present PIRT is aimed to utilize for validation of the sodium fire analysis codes. Because a sodium fire accident in an SFR plant involves complex phenomena, various figures of merit (FOMs) for importance ranking could exist in the PIRT process. Therefore, the FOMs are specified through factor analysis. Associated phenomena in a sodium fire event are identified through the element- and sequence-based phenomena analyses. Importance of each associated phenomenon is evaluated by considering the sequence-based analysis of associated phenomena related to the FOMs. Then, ranking table in a sodium fire event is established. In order to validate models corresponding to the identified important phenomena in the sodium fire analysis codes, an assessment matrix of important phenomena and experiments is completed finally.

Key Words: Sodium Fire, PIRT, Verification &Validation, Assessment Matrix

1. Introduction

A sodium fire accident is one of key issues in sodium-cooled fast reactor (SFR) plants when sodium leaks out of a coolant circuit since sodium has high chemical reactivity with oxygen and moisture. The sodium fire may harm the plant itself and the circumference environment because of the reaction heat and aerosol of reaction products. In order to evaluate the consequence of the sodium fire event, sodium fire analysis codes have been developed such as SPHINCS [1] and AQUA-SF [2]. Validation of models in these codes would be more appropriate by identification of key phenomena during sodium fire events. The PIRT (Phenomena Identification and Ranking Table) process is an effective method to identify key phenomena involved in an interesting event [3]. One of significant milestones in a PIRT process is identification of important phenomena. So far, we have completed a ranking table of important phenomena involved in a sodium fire accident in an SFR through a PIRT process with factor and phenomenon analyses [4]. It is effective for systematical validation base on the PIRT result to arrange a validation matrix which involves relation between models in an analysis code corresponding to the identified important phenomena and experimental data to validate the models. This paper describes the validation matrix of important phenomena and experiment for the sodium fire analysis codes in addition to the essential of the ranking table [4] of important phenomena through the PIRT process for sodium fire events. PIRT process to complete the ranking table consists of following three steps: specification of figures of merit (FOMs), identification of phenomena associated with sodium fire accidents and importance evaluation of the identified phenomena. Experimental data utilized to validate the sodium fire analysis codes SPHINCS and AQUA-SF are arranged in the assessment matrix where models in the analysis codes are corresponded to the important phenomena.

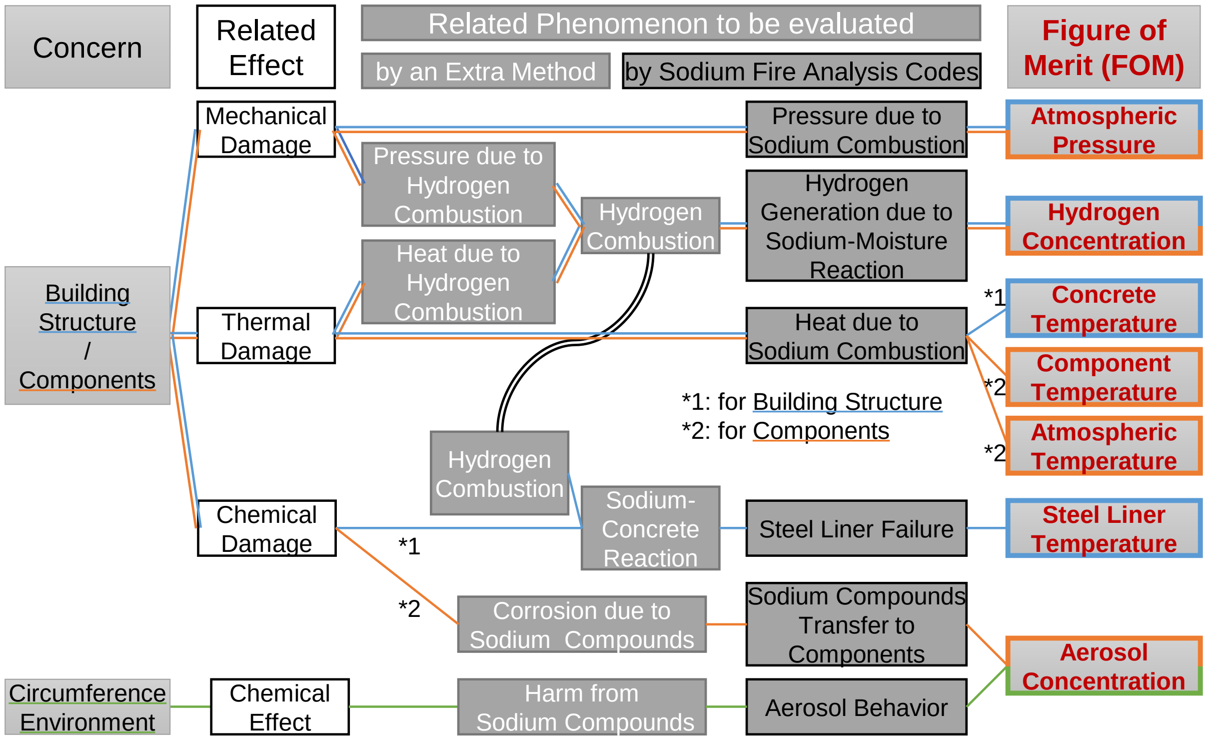

FIG. 1. Chart of the factor analysis related to sodium fire accident [4]

2. Ranking Table

2.1. Specification of Figures of Merit

Evaluating scenario in this PIRT process is initialing from sodium leakage from a secondary coolant circuit in a plant building room that consists of concrete structure, steel lined floor, ambient air and reactor components including piping of the coolant circuit. Combustion of sodium and resulting transfer of heat and mass are considered. Range of considering phenomena which is determined through factor analysis is limited to those to be evaluated by sodium fire analysis codes. The primary purpose of the factor analysis is to specify appropriate FOMs from concerns in sodium fire accidents. Since a sodium fire accident in an SFR involves complex phenomena, various FOMs could exist in this PIRT process. Actually, two FOMs were specified in the PIRT process of a sodium fire accident in JAEA [5]. In the PIRT process in SNL [6], both thermal and aerosol insult was concerned although the FOM was unified to one as the ability to predict the both insult. In order to specify FOMs in this PIRT process, we consider concerns about building structure, components and circumference environment resulting from sodium fire in the factor analysis. Here, the concern about circumference environment denotes influence on living bodies in and around the plant. Factors and relevant phenomena are analyzed for each concern as shown in FIG. 1 and explained below.

Factors relevant to the concern about building structure has several features including mechanical, thermal and chemical damage. A further factor behind the mechanical damage is pressure rise due to sodium combustion and hydrogen combustion. Thus, atmosphere pressure becomes one of FOMs simply. We discriminated the identified factors on the basis of whether each factor should be evaluated by sodium fire analysis codes or by an extra method. Whereas hydrogen combustion is not to be evaluated by sodium fire analysis codes, sodium fire analysis codes should quantify hydrogen generation. As the result, hydrogen concentration is also identified as an FOM. The thermal damage is also triggered by both sodium and hydrogen combustion. Then, concrete temperature in the structure is listed as an FOM. Considerable chemical damage of the concrete structure is sodium-concrete reaction which is evaluated beyond sodium fire analysis codes. Since sodium contacts with the concrete only after penetrating the steel liner on the concrete, liner temperature is specified as an FOM. FOMs relevant to the concern about components and circumference environment are also specified through the same manner with the factor analysis.

Seven FOMs in total are specified in this PIRT process with the factor analysis by considering concerns resulting from sodium fire as presented in FIG. 1. Here, atmospheric temperature is substituted for component temperature as an FOM for the concern about components related to thermal damage in accordance with the general fire Probabilistic Risk Assessment [7]. This is because zone model codes such as SPHINCS analyze just averaged temperature of atmosphere in an evaluating room, local temperature of each component is difficult to be evaluated by zone model codes.

2.2. Identification of Phenomena Associated with Sodium Fire Accidents

This section describes a methodology to identify associated phenomena that are listed in the first row of the ranking table. Associated phenomena are identified based on both the element- and sequence-based phenomena analyses. The element-based phenomena analysis where a system such as an SFR plant is decomposed hierarchically [8] has been widely used in PIRT processes [9][10]. In the sequence-based phenomena analysis, associated phenomena are identified by analyzing an event progression as presented in a literature [11]. The lists of associated phenomena identified by the element- and sequence-based analyses are confirmed to be consistent each other for making it more adequately.

In the element-based phenomena analysis as shown in FIG. 2, an SFR plant is hierarchically decomposed into its subsystem, module, component, phase, geometry, field and transfer process. Then, associated phenomena are identified from the transfer process. We focus just a building room in a secondary cooling system as a typical sodium fire event in this PIRT process. Considerable components in the building room are ambient air that exists originally, aerosol of sodium compounds, hydrogen generated by sodium reaction, steel liner on the floor, concrete of building structure and leaked sodium. Aerosol and hydrogen components which exist as mixture with ambient gas are distinguished from ambient gas because they come in only after combustion of leaked sodium. Each component is decomposed into a phase of gas, liquid or solid. The concrete component has the liquid phase in addition to the solid one, since the concrete contains inside water which is released by heating. Aerosol of both the liquid and solid phases exists as very small particle together. Leaked sodium is divided into the droplet or column state in the air and the pool state on the floor. All the elements have their heat energy field. The gas and liquid phases have also mass and momentum fields. The mass field is considered in the steel liner component because its thickness changes due to corrosion wastage. The mass field of water contained in concrete is also considered. The transfer processes involved in sodium fire events are categorized into combustion of sodium including reaction with moisture, heat and mass transfer and chemical reactions in atmosphere and with structure. Then, transfer process and associated phenomena are identified for each category. As the result of the element-based phenomena analysis, fourteen associated phenomena are identified as listed in FIG. 2.

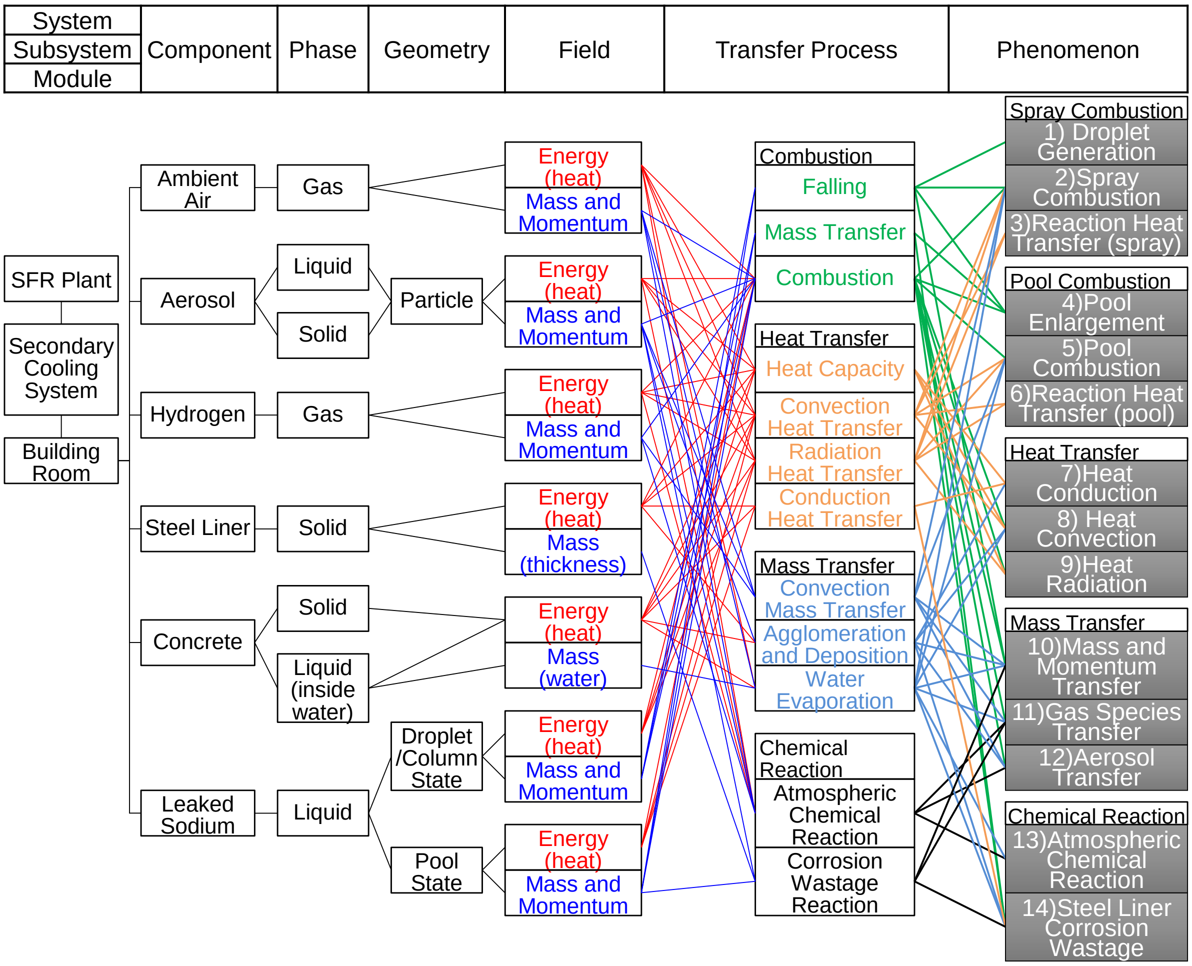

FIG. 2. Hierarchical system decomposition chart of element-based phenomena analysis [4]

The associated phenomena is also identified through sequence-based analysis in addition to the element-based one for making it more adequately. FIG. 3 shows the chart of whole event sequence studied in the sequence-based analysis. Importance ranking indicated in FIG. 3 is explained in the next section. The event sequence is initiated by sodium leakage from a cooling system into a building room. The leaked sodium forms into droplets. Then, spray combustion occurs involving sodium-moisture reaction. Since some of leaked sodium falls to a floor without combusting, a sodium pool is formed and pool combustion occurs on the floor. As the result of the spray and pool combustion, heat and reaction products are generated. Reaction heat is transported to the sodium droplets, pool and circumference atmosphere by heat convection and radiation. Direct heat transfer to the structure also occurs through heat radiation. Heat conduction, which is negligibly little contribution in atmosphere, transfers the heat between the sodium pool and the structure and in the structure. Heat transfer to steel liner affects its corrosion wastage. Mass and momentum transfers are driven by buoyancy as consequence of thermal expansion of atmosphere. Then, convection transfers of heat and mass are promoted. The sodium reaction with oxygen generates its oxides and the reaction with moisture generates hydrogen and sodium hydroxide, respectively. The sodium oxides and hydroxide become aerosol mixing with atmosphere. Therefore, convection of mixed gas transfers these reaction products. Amounts of the hydrogen and sodium oxides change due to their chemical reaction with oxygen and moisture in atmosphere, respectively. The amount of aerosol is also affected by agglomeration, deposition to a solid surface and falling to a pool surface. As the result of the sequence-based phenomena analysis, the same associated phenomena are identified as those by element-based one listed in FIG. 2.

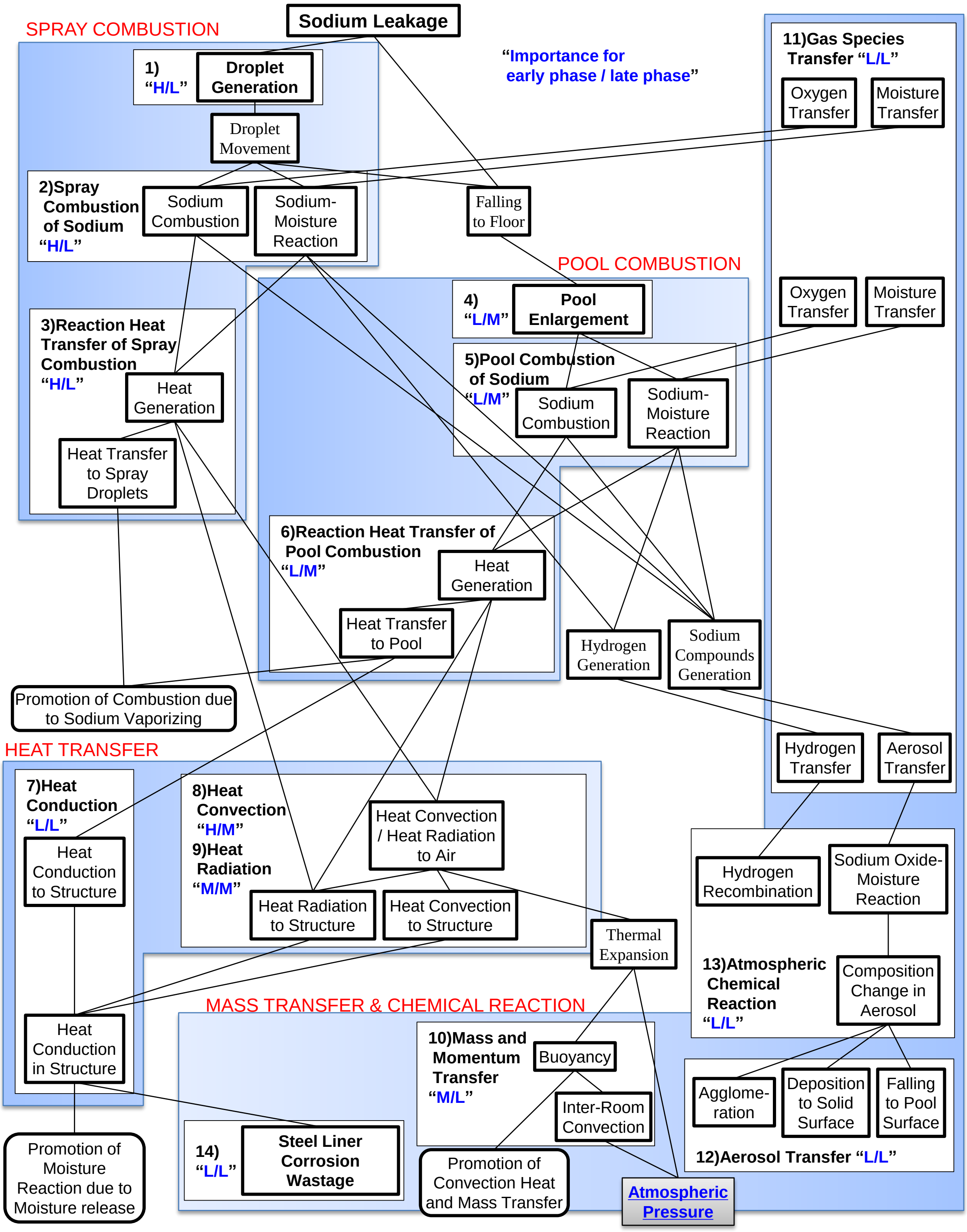

FIG. 3 Chart of event sequence in a sodium fire accident as the result of sequence-based phenomena analysis with importance of each phenomenon for atmospheric pressure

TABLE I: RANKING TABLE IN SODIUM FIRE PHENOMENA [4]

Category	Phenomenon (Related Concern* / Figure of Merit)	Atmospheric Pressure	Concrete Temperature	Component Temperature	Atmospheric Temperature	Steel Liner Temperature	Hydrogen Concentration	Aerosol Concentration
	Related Concern*	1&2	1	2	2	1	1&2	2&3
Spray Combustion	1) Droplet Generation	H/L	M/L	M/L	H/L	M/L	L/L	H/M
	2) Spray Combustion	H/L	M/L	M/L	H/L	M/L	L/L	H/M
	3) Reaction Heat Transfer (spray)	H/L	M/L	M/L	H/L	M/L	L/L	L/M
Pool Combustion	4) Pool Enlargement	L/M	L/M	L/M	L/M	L/M	L/M	L/M
	5) Pool Combustion	L/M	L/H	L/H	L/M	L/H	L/M	L/M
	6) Reaction Heat Transfer (pool)	L/M	L/H	L/H	L/M	L/H	L/L	L/L
Heat Transfer	7) Heat Conduction	L/L	H/H	H/H	L/L	H/H	L/M	L/L
	8) Heat Convection	H/M	M/M	L/M	M/H	L/M	L/M	L/M
	9) Heat Radiation	M/M	M/M	L/M	M/M	L/M	L/M	L/L
Mass Transfer	10) Mass and Momentum Transfer	M/L	L/L	L/L	L/M	L/L	L/M	M/H
	11) Gas Species Transfer	L/L	L/L	L/L	L/L	L/L	H/H	M/M
	12) Aerosol Transfer	L/L	L/L	L/M	L/L	L/M	L/M	H/H
Chemical Reaction	13) Atmospheric Chemical Reaction	L/L	L/L	L/L	L/L	L/L	L/M	L/M
	14) Steel Liner Corrosion Wastage	L/L	L/L	L/L	L/L	H/H	L/L	L/L

*Concern about 1)Building Structure, 2)Components and 3)Circumference Enviroment

2.3. Importance Evaluation of the Identified Phenomena

Importance of the associated phenomena are evaluated in view of their contribution for the maximum value of the FOM. For this purpose, the FOMs are arranged in the event sequence chart as illustrated in FIG. 3, only atmospheric pressure here as a representative example. The importance of each phenomenon is evaluated by reference to the event sequence chart in addition to the engineering judgment. Importance of both early and late phases is considered. In the early phase, spray combustion is dominant over pool combustion. When pool combustion becomes dominant because of pool enlargement and oxygen deficiency around spray fire region, the event transits to the late phase. In the early phase, droplet generation, spray combustion of sodium and reaction heat transfer of spray combustion are judged as *high* importance. In the late phase, the phenomena categorized pool combustion become dominant over those spray combustion but ranked as *medium* importance because pool combustion is less intense reaction than spray combustion. Reaction heat generated by spray and pool combustion transfers to ambient air in the building room. Then, atmospheric pressure increases due to thermal expansion of the air. Processes of heat transfer to the air are convection and radiation. Thus, heat convection and radiation are judged as *high* or *medium* importance. The heat convection in the early phase is the dominant process of heat transfer over the maximum atmospheric pressure and hence judged as *high* importance. Mass and momentum transfer is ranked with *medium* importance because this phenomenon promotes convection heat transfer and in addition, the inter-room convection decreases atmospheric pressure in the building room.

The importance evaluation for the other six FOMs is conducted with the same manner. The overall result of importance ranking is shown in TABLE I. Key points of the importance evaluation is described below. The importance judgment for atmospheric temperature is very similar to that for atmospheric pressure since the most of associated phenomena are common for the atmospheric pressure and temperature. Phenomena of higher importance for component, concrete and steel liner temperature are heat conduction and those categorized pool combustion. This is because heat transfer process to the structures is mainly heat conduction from pool combustion heat. For hydrogen concentration, transfer of gas species including moisture and hydrogen is the most important phenomenon since hydrogen is generated by sodium-moisture reaction and then transfers to ambient air. Hydrogen concentration is also influenced by heat conduction to concrete which increases moisture concentration and by aerosol transfer which decreases it. Importance for hydrogen concentration in the later phase are ranked as higher rank since hydrogen concentration increases slowly especially before starting moisture release form concrete. For aerosol concentration, spray combustion is the dominant phenomenon in the early phase for the same reason as that for atmospheric pressure. However, because the aerosol concentration is likely to keep increasing for a longer time, mass and momentum transfer in the late phase is also identified as phenomenon of high importance.

TABLE II: ASSESSMENT MATRIX OF IMPORTANT PHENOMENA AND EXPERIMENTS

Phenomenon & Rank*1		**Model**		**Experiment**					
				Spray Fire		Pool Fire			
		SPHINCS	AQUA-SF	Single Droplet (FD)	Spray (Run-E1)	Constant Pool Area (Run-D1)	Enlarging Pool Area (Run-F7)	Multi-cell Pool (Run-D3)	Integrated Mock-up (Run-D4)
1) Droplet Generation	H	Nukiyama-Tanasawa Model		-*4	-*4	-*4	-*4	-*4	-*4
2) Spray Combustion*2	H	Spray Combustion Model (NACOM)		✓	✓		n/a*5		n/a*5
3) Reaction Heat Transfer (spray)	H				✓		n/a*5		n/a*5
4) Pool Enlargement	M	Governing Equations for Droplet Falling and Unburnt Pool					✓		✓
5) Pool Combustion*2	H	Flame Sheet Combustion Model			n/a*5	✓	✓	✓	✓
6) Reaction Heat Transfer (pool)	H				n/a*5	✓	✓	✓	✓
7) Heat Conduction	H	Governing Equation of Heat Conduction			✓ *6	✓	✓	✓	✓
8) Heat Convection	H	Flow Network Model	CFD		✓ *6	✓ *6	✓	✓	✓
9) Heat Radiation	M	Radiation Model	6-Flux Gas Radiation Model			✓	✓ *6	✓ *6	✓ *6
10) Mass and Momentum Transfer	H	Flow Network Model & Water Release Model from Concrete	CFD & Water Release Model from Concrete					✓	
11) Gas Species Transfer	H							✓	✓
12) Aerosol Transfer	H	Flow Network Model	CFD			✓	✓	✓	✓
		Agglomeration and Deposition Models							
13) Atmospheric Chemical Reaction	M	Equilibrium Reaction Model							✓
14) Steel Liner Corrosion Wastage	H	(NaFeO type Corrosion Model)*3		-*4	-*4	-*4	-*4	-*4	-*4

*1: Highest rank of each phenomena in the ranking table
*2: Including sodium-moisture reaction
*3: Out of range in the present sodium fire evaluation
*4: Out of range in the present matrix
*5: Negligible small influence
*6: Assessable but indirect measurement

3. Assessment Matrix of Important Phenomena and Experiments

3.1. Models in the Sodium Fire Analysis Codes

TABLE II shows assessment matrix of the models in the analysis codes SPHINCS and AQUA-SF corresponding to the important phenomena and the experimental data to validate the models. All the important phenomena are modelled in both the SPHINCS and AQUA-SF codes except for steel liner corrosion wastage which can be evaluated by means without the sodium analysis codes. While the spray and pool combustion models are common in both the codes, spatial dimension of atmosphere is the largest difference between the codes. In the SPHINCS code employed a zone model for fast calculation, one computational cell, or several ones when needed, is applied for one room in a reactor building. Temperature and concentration of gas species are homogenized in the atmosphere of a room. Then, inter-room transfer of momentum, mass and heat is calculated by the flow network model based on the conservation of momentum, mass and heat energy considering momentum transfer due to pressure gradient and buoyancy. On the other hand, the AQUA-SF, which is based on a three dimensional CFD code AQUA, calculates intra-room transfer of temperature and gas species as well as inter-room transfer.

3.2. Sodium Fire Analysis Experiments

Numerous experimental studies have been performed for sodium fire investigation. We select six representative experiments performed in JAEA for validation data involving the key phenomena in sodium fire events as listed in TABLE II. The FD series experiment is a basic falling test of a single sodium droplet involving combustion in air atmosphere [12][13][14]. Spray combustion model can be assessed by the FD experiment data. Run-E1 is a large-scale spray fire experiment where sodium was sprayed into a closed cylindrical vessel [15]. Temperature distribution and pressure change in the vessel was measured in this experiment. These experimental data is available for validation of spray combustion model and heat conduction and convection models. The Run-D1 experiment is a basic pool fire experiment where sodium was supplied from the bottom of the pool and the pool area was constant during the most of the experiment [16]. An important feature of this experiment is the measurement of heat flux from the combusting pool. Evaluation of heat radiation is enabled by this feature. In the Run-F7 experiment, sodium was supplied from nozzle above the pool with column state flow and then pool area enlarged as well as conceivable sodium leakage accidents [17][18]. Heat and aerosol transfer resulting from pool fire is investigated as is the case in Run-D1. A multi-cell facility was utilized in the Run-D3 experiment [19]. An adjoining room was connected to the room used in the Run-D1 pool fire experiment through a horizontal slit. Inter-cell heat and mass transfer can be investigated by this experiment. The Run-D4 experiment simulated the structural objects in the Monju plant such as an air duct and a grating to investigate the sodium fire incident in 1995 [20][21]. The experimental data is used for comprehensive validation of the codes. It is notable that water release from concrete and resulting atmospheric chemical reaction of moisture and sodium oxides were observed in this experiment performed in a concrete structure.

The assessment matrix of important phenomena and experiments is common in the zone model code SPHINCS and the three-dimensional field model code AQUA-SF since the important phenomena is identified without relation to analytical codes. However, detailed assessment is considered to be needed for the three-dimensional code as described in the following section.

3.3. Specific Validation for the Three-dimensional Code

The three-dimensional code AQUA-SF has a CFD module which can analyze detailed thermal-hydraulic behavior. The CFD module should be assessed without sodium fire as for more careful assessment. A basic thermal-hydraulic phenomenon during a sodium fire event is buoyancy convection due to sodium combustion heat followed by convective heat and mass transfer. As for fundamental assessment, thermal cavity problem [22] is an appropriate benchmark to validate the thermal-hydraulics models which is equations coupling of mass, momentum and energy conservation laws. Another important phenomenon is turbulence. Airflow during sodium fire event is expected to be turbulent especially in the case of intense sodium combustion. A turbulent plume experiment dominated by buoyant convection with thermal effect [23] is a suitable for validation of the turbulence model in the sodium fire analysis code. Moreover, some sodium fire experiments listed in TABLE II provides useful data related to multi-dimensional effects. For instance, thermo-couple trees are used in the Run-E1 experiment to measure spatial temperature distribution. It is possible to assess multi-dimensional effects by means of these transient data of thermo-couple trees.

4. Conclusions

For the validation of the sodium fire analysis codes SPHINCS and AQUA-SF, the ranking table and the assessment matrix of important phenomena were completed through the PIRT process of a sodium fire accident. Seven FOMs were specified by the factor analysis. Associated phenomena were identified through both the element- and sequence-based analyses for adequate phenomena identification. As the result, fourteen phenomena were listed in the ranking table. Importance of the identified phenomena was evaluated by reference to the event sequence chart where the FOMs were corrected with the phenomena in addition to the engineering judgment. Through complement of the assessment matrix, we confirmed sufficiency of models in the codes corresponding to the important phenomena. Six sodium fire experiments for validation were listed covering the key phenomena. Validation for the CFD module in the three-dimensional code were also considered in addition to the validation matrix.

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