Possibility of process-oriented training toward enhancing operators' resilience – preliminary consideration based on a study in air traffic control domain –

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Abstract: For the purpose of achieving a higher level of nuclear safety, a key issue is to develop training methods for enhancing the abilities of nuclear power plant personnel to respond resiliently to uncertain and changing situations. Toward addressing the issue, this paper discusses the importance and possibility of operators' training focusing not only on the outcome but also on their working processes from technical and non-technical perspective. As reference for the preliminary consideration on such training methods for plant personnel, research on the visualization of Air Traffic Control (ATC) processes for supporting controllers' training is introduced. Based on perspectives and experience obtained through the research, possible suggestions for enhancing the training methods of plant personnel are presented.

Keyword: safety; resilience; education and training; air traffic control

1 Introduction

The accident of Fukushima Daiichi Nuclear Power Plant occurred on March 11, 2011 and the devoted efforts by the plant personnel to mitigate the accident outcome strongly indicates the importance of human ability to respond resiliently to challenging situations involving changing conditions, time pressure, insufficient information, *etc.*, in emergency countermeasures [1]. Not only in such critical situations but also in daily operations, the essential role of human contribution in maintaining both safety and productivity is again recognized in a safety perspective discussed in Resilience Engineering [2][3] and Safety-II [4]. For achieving a higher level of nuclear safety, a key issue is to develop training methods for enhancing the abilities of plant personnel to respond resiliently to uncertain and changing situations. According to Resilience Engineering, resilience is defined as *"the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions"* [3]. The ability of resilience can lead to resilient performance, which can play an important role in handling unprepared situations. In this paper, the words of "resilient" and "resiliently" are also used for expressing resilient performance, that is, performance being adjusted to handle changes and disturbances which are uncovered by the design and procedures of systems. The purpose of this paper discusses the importance and possibility of operators' training focusing not only on the outcome but also on their working processes from technical and non-technical aspects toward enhancing operators' resilience. As reference for preliminary consideration of such training methods for plant personnel, this paper introduces research on the visualization of Air Traffic Control (ATC) processes for supporting controllers' training carried out by the authors. The highest priority objective of ATC services is to maintain air traffic safety by assuring minimum separation between any two aircraft following separation standards. However, in actual operations, controllers are required to achieve not only the safety goal but also productivity goals such as the efficiency and expeditiousness of traffic flow. Controllers simultaneously achieve the multiple and possibly conflicting goals by their performance adjustments to dynamic and changing situations. That is, ATC operations are characterized as adaptive and resilient responses by controllers, which is considerably different from the operations of nuclear power plants in prepared situations characterized as standardized and manual-based operations. However, also in the nuclear domain, the importance of training and drills for cultivating the abilities of plant personnel to

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respond resiliently is mentioned for managing challenging situations beyond preparedness such as the Fukushima accident [5]. Not only in severe accident situations but also in normal operations, the abilities are required to address inevitable potential safety risks such as human errors of team members. Therefore, the authors believe that perspective and experience obtained through the research toward supporting controllers' training can be informative for enhancing the training programs and methods of plant personnel in the nuclear domain.

In this paper, Section 2 presents the further explanation of ATC tasks. Section 3 describes the overview of tools and methods to visualize ATC processes developed by our research group. Section 4 introduces an example of the visualization and analysis of ATC processes. In Section 5, possible issues for the enhancement of training programs for nuclear power plant personnel are discussed.

2 ATC tasks and studied sectors

As noted in Section 1, the purpose of ATC services is to promote the safe, orderly and expeditious flow of air traffic. Although ATC services cover aircraft on the ground and in airspace, en-route air traffic control studied in our research is provided for in-flight aircraft as a part of ATC services. In en-route ATC, airspace is divided into smaller spaces called sectors. A team of controllers consisting of a radar controller and a coordinator takes charge of ATC services in each sector.

In our research, sector T09 and sector T14 in Japan are studied. As shown in Fig. 1, the sectors are adjacent and located in the western part of the Tokyo region. The distance from the western boundary of sector T09 to the eastern boundary of sector T14 is approximately 170 nautical miles (NM). The maximum north-south distance is about 50 NM. The small white circle in Fig. 1 indicates a fix which is a geometrical point used for aiding in air navigation. The capital letters near the white circle, that is, ADDUM, is the name of the fix.
Sector T09 and sector T14 are two of the busiest sectors in Japan. The controllers of these sectors handle approximately 450-500 flights per day in this relatively small area. Dominant traffic in these sectors are arrival flights to Tokyo (Haneda) Airport coming from airports located in the western part of Japan. There are several principal routes of the arrival flights as indicated in Fig. 1. The controllers of these sectors are required to form aircraft flying on respective routes in line with prescribed in-trail separation between a leading aircraft and a following aircraft, in addition to assuring minimum separation of 5 NM horizontally or 1,000 feet vertically between each two aircraft.

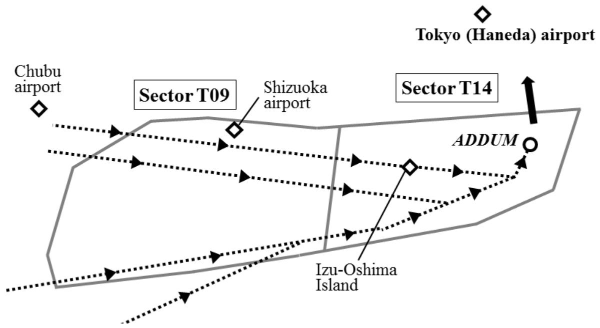

Fig.1 Studied ATC sectors.

In sector T09 and sector T14, a special ATC operation method in which controllers of two consecutive ATC sectors cooperatively complete necessary ATC tasks for each aircraft has been introduced for handling a large amount of air traffic efficiently while regulating controllers' workload. Therefore, the target states of the arrival flights to Tokyo Airport are set only in sector T14, which are at 7NM in-trail separation and 10,000 feet in altitude by the ADDUM point (see Fig. 1). The arrival flights can be handed off from sector T09 to sector T14 on the way to achieve their target states. In other words, the controllers of the two sectors cooperatively share necessary ATC tasks to achieve aircraft's target states.

3 Visualization methods and tools

3.1 Background

In order to meet the growing demand of air traffic in recent years, skilled controllers are definitely required. Therefore, the efficient training of controllers is an urgent issue in the ATC domain. However, skill transfer from experienced controllers to ATC trainees is difficult partly because the working processes of the experienced controllers are based on their implicit knowledge acquired through their working experiences. It means that the reasons and purposes of their working processes, that is, why an ATC instruction is necessary at that time and what effects are brought about by the instruction on the future air traffic situations, are hard to understand for the inexperienced trainees. For resolving this difficulty in ATC training, our research group has developed a process visualization tool of ATC tasks called COMPASi (COMPAS in interactive mode / COMPAS: COgnitive system Model for simulating Projection-based behavior of Air traffic controllers in dynamic Situations) [6][7]. COMPASi is capable of visualizing controllers' working processes, which is expected to reveal the effects of control strategies and specific ATC instructions on the air traffic situations through the comparative analysis of multiple working processes. In the following two sections, the overview of the functional features of COMPASi is presented.

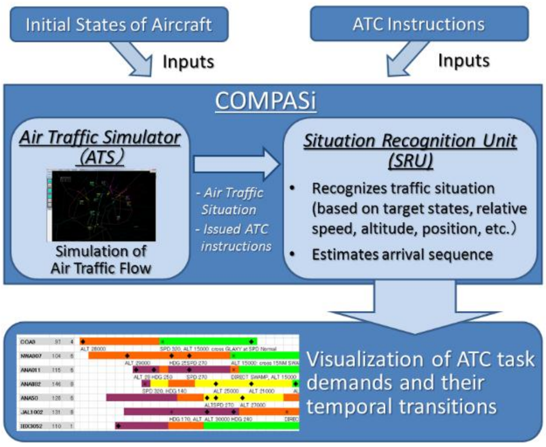

Fig.2 Conceptual diagram of COMPASi (adapted from [7]).

3.2 Visualization of ATC task demands

Figure 2 shows the conceptual diagram of COMPASi. COMPASi is an ATC simulation and visualization tool equipped with the Air Traffic Simulator (ATS) and the Situation Recognition Unit (SRU). Given the initial states of traffic (for example: aircraft's initial position, altitude, indicated air speed, and so on) and the log of ATC instructions, ATS simulates air traffic flows with the continuous performance calculation of aircraft and the issuing of ATC instructions. The simulated air traffic situations are analyzed by SRU using a stored rule-base, and required ATC tasks are automatically detected and classified according to the ATC task index shown in Table 1, entitled "Task Demand Levels (TDL)".

Table 1 Task Demand Levels (TDLs) (adapted from [8])

Lv.	Situation / Task Demand	Display Color on COMPASi
4	time-critical situation in terms of conflict resolution(s)	Red
3++	multiple separation assurances (conflict resolution(s) / in-trail spacing) between the target aircraft and three or more related aircraft	Magenta
3+	multiple separation assurances (conflict resolution(s) / in-trail spacing) between the target aircraft and two related aircraft	Orange
3	separation assurance (conflict resolution / in-trail spacing) between the target aircraft and one related aircraft	Light Beige
2	altitude change	Light Blue
1+	ATC tasks are completed, but the target aircraft is in speed adjustment.	Green
1	ATC tasks are completed.	Light Green

TDLs consist of 7 levels reflecting necessary ATC tasks for each aircraft. Aircraft coming from upstream sectors have various levels of TDLs ranging from Lv.1 to Lv.3++. By completing necessary ATC tasks in a sector in question, the TDL of each aircraft lowers to Lv.1. That is, TDLs of all aircraft have to be at Lv.1 before they are handed off to downstream sectors. TDL describes the execution states of ATC tasks by the lowering process from higher levels to Lv. 1. COMPASi outputs TDLs as color-coded aircraft symbols and call signs on the simulated radar display (see Fig. 3) and the time series graph called Chart of ATC task Processing State (CAPS) (see Fig. 4). In addition, CAPS contains information of contents and timings of ATC instructions (Fig. 4(a)), flight distances (Fig. 4(b)), and the numbers of instructions (Fig. 4(c)). CAPS visualizes the ATC task process of a controller by presenting issued ATC instructions and situation changes resulting from the instructions along the timeline. COMPASi and CAPS were utilized in analytical research of performance characteristics of multiple air traffic control strategies adopted by controllers [7].

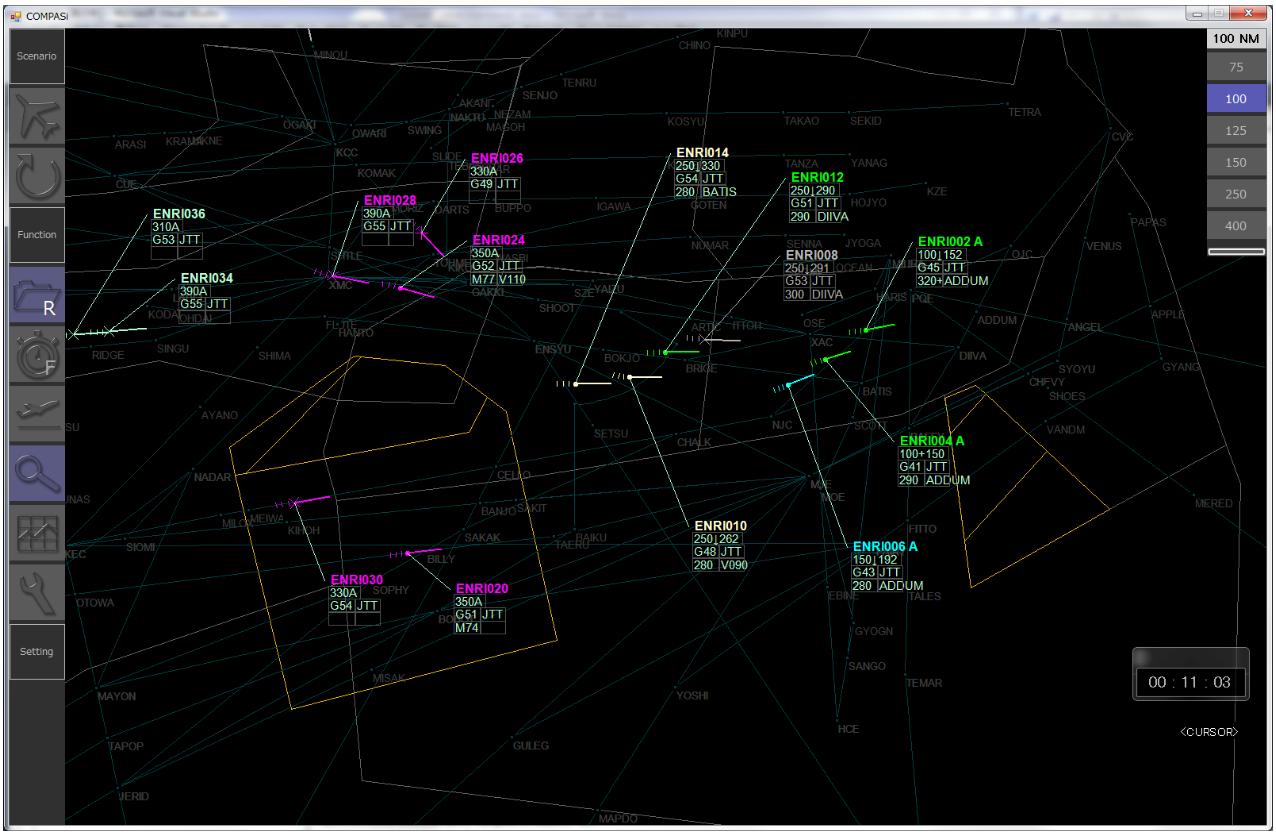

Fig.3 Simulated radar display of COMPASi.

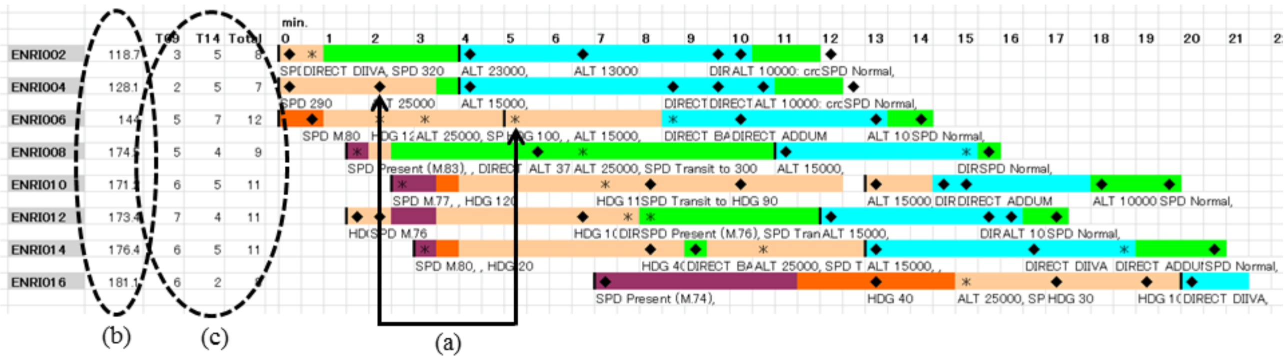

Fig.4 Chart of ATC task Processing State (CAPS) (adapted from [9]).

3.3 Visualization of process of in-trail spacing

In addition to the visualization of ATC task demands, COMPASi also has functionalities to output data for visualizing the detailed process of in-trail spacing, which is a major ATC task for assuring prescribed separation between related arrival flights. In-trail spacing can be regarded as the appropriate adjustment of the arrival time at a specific target fix of the related flights by issuing ATC instructions such as speed adjustment, vectoring, and so on. Therefore, a time-series line chart of the remaining flight distance to the transfer fix of each flight (see Fig. 5 as an example) reflects the features of the in-trail spacing process. In the time-series line chart called “Time-series chart of Remaining flight distance for Analyzing Control Effect to arrival traffic (TRACE)” proposed by our research group, efficient in-trail spacing is depicted by the rapid increase of the distances of polygonal lines since the distances correspond to the separations between respective flights. On the contrary, continuous closely-spaced polygonal lines (Fig. 5 (a)) indicate a situation where it took time to establish required in-trail separation. The gradient of a polygonal line of TRACE reflects the approaching rate of an aircraft to the target fix. For example, the effects of ATC instructions for putting off the arrival time at the target fix, such as the reduction of air speed and/or the extension of flight distance, are indicated by the gentle gradient of the polygonal line (Fig. 5 (b)). Conversely, ATC instructions for advancing the arrival time, such as "direct-to" instructions, cause the steep gradient of the polygonal line (Fig. 5 (c)). In short, the gradient of each line can reflect the effects of the adjustments of traffic situations carried out by a controller.

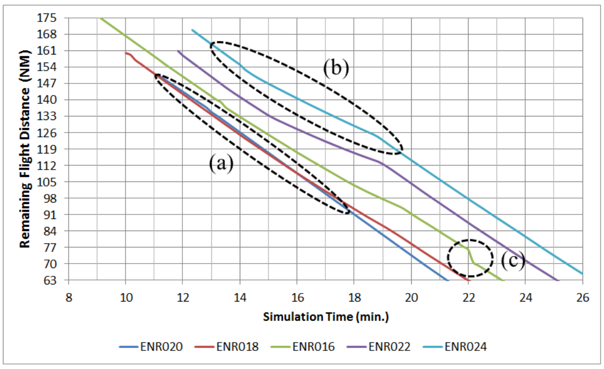

Fig.5 Example of Process Visualization of In-trail Spacing[9]

4 Analysis and results[9]

This section shows the analysis results of in-trail spacing processes derived from a high-fidelity Human-In-The-Loop Simulation (HITLS) as an analysis example using COMPASi.

4.1 Traffic Scenario

Figure 6 shows the traffic scenario analyzed here. It is a part of the traffic scenario which was used in a high-fidelity HITLS of sector T09 and sector T14, carried out in June, 2012, with the cooperation of Tokyo Area Control Center. As indicated by the dashed white circle in Fig. 6, in this situation, 7 NM of in-trail separations between 4 aircraft ENR008, ENR010, ENR012, and ENR014 need to be assured. Two types of controllers' working processes to resolve the in-trail spacing task were extracted from the recorded data in the HITLS (In the later part, they are called "Process-A" and "Process-B", respectively). A major difference between Process-A and Process-B is the arrival sequence of the objective flights (See Table 2). The controllers' working processes addressin the in-trail spacing tasks have been replicated and analyzed using COMPASi.

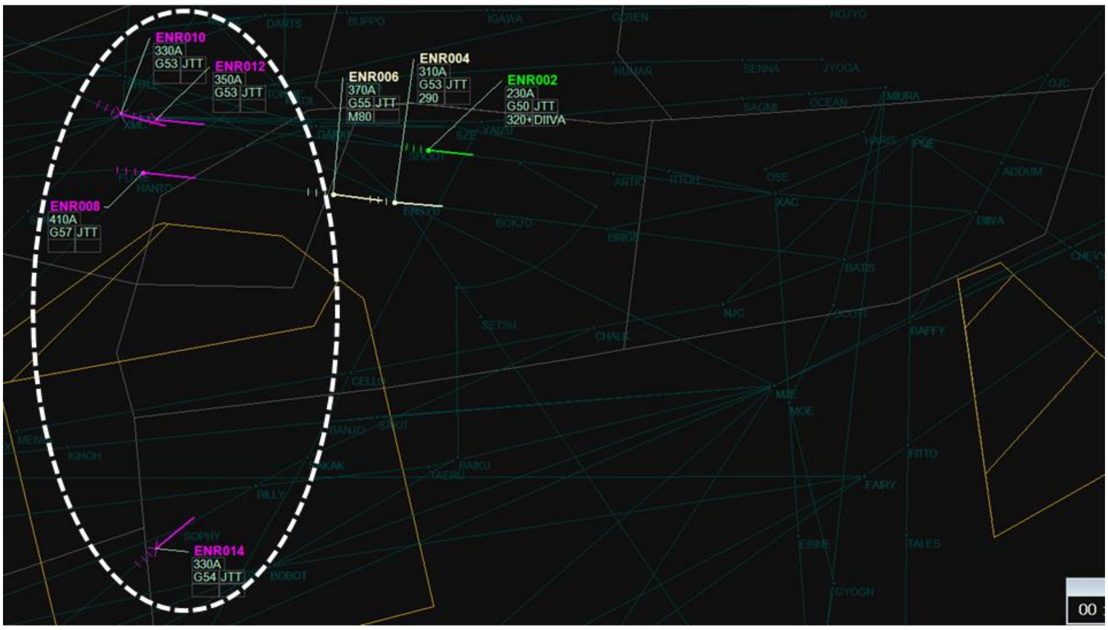

Fig.6 Analyzed traffic scenario[9]

Table 2 Arrival sequence of Process-A and Process-B[9]

	1	2	3	4
Process-A	ENR008	ENR012	*ENR010*	*ENR014*
Process-B	ENR008	ENR012	*ENR014*	*ENR010*

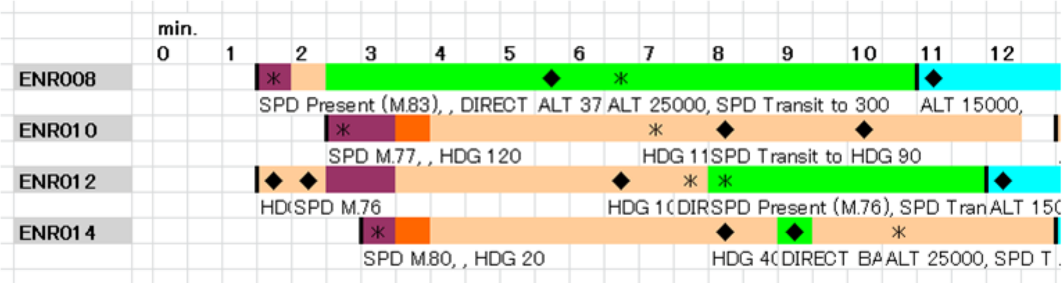

Fig.7 CAPS of Process-A[9]

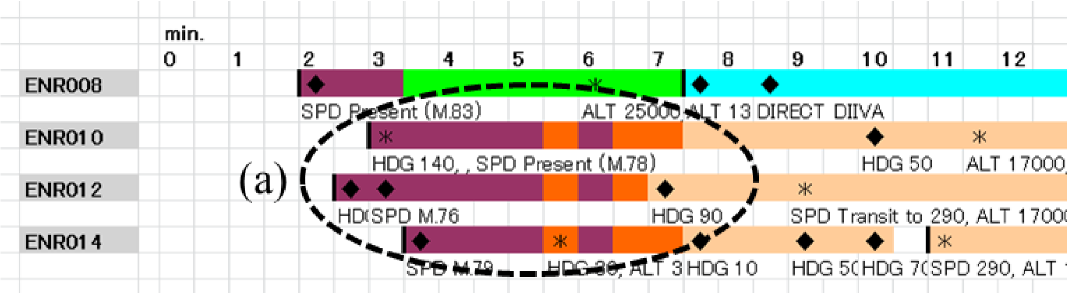

Fig.8 CAPS of Process-B[9]

4.2 Results

As compared to the CAPSs of Process-A and Process-B presented in Fig. 7 and Fig. 8, the duration of relatively higher levels of TDLs is shown in Process-B (Fig. 8(a)). It means that more complex traffic situations lasted in Process-B. For identifying the probable cause, Process-A and Process-B have been comparatively analyzed using TRACE (Fig. 9 and Fig. 10). Small circles on each polygonal line in Fig. 9 and Fig. 10 indicate the time points when the controller of sector T09 issued one or more ATC instructions for assuring in-trail separation, that is, vector, speed, or direct-to instructions, to the aircraft. The initial point of each polygonal line corresponds to the time point of initial contact from the aircraft to the controller of sector T09.

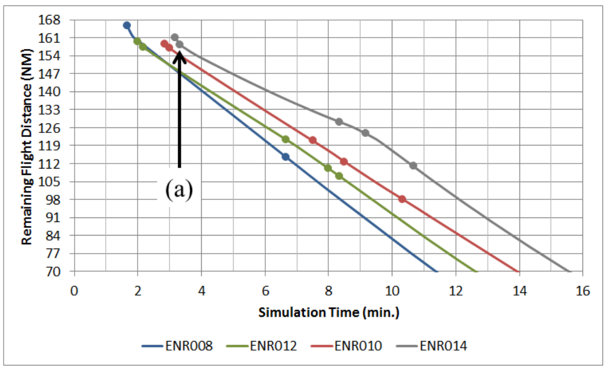

Fig.9 Process of In-Trail Spacing (Process-A) [9]

According to Fig. 9, the arrival sequence of the target flights of Process-A (See Table 2) is in order of the remaining distance to the target fix of respective flights (In this case, the target fix is the ADDUM point indicated in Fig. 1). Although the approach rate to the ADDUM point of ENR014 (following aircraft in this case) is relatively high at the initial point, the separation between ENR010 (leading aircraft in this case) and ENR014 is assured by the ATC instruction to ENR014 issued at the time point of approximately 3 min. in order to reduce its approach rate (Fig. 9(a)). On the other hand, in Fig. 10, the polygonal lines of ENR010 and ENR014 cross at the time point of 6 min. (Fig. 10(b)), which means that the exchange of the positions of ENR010, leading aircraft with lower ground speed, and ENR014, following aircraft with higher ground speed, is required to achieve the arrival sequence of Process-B.

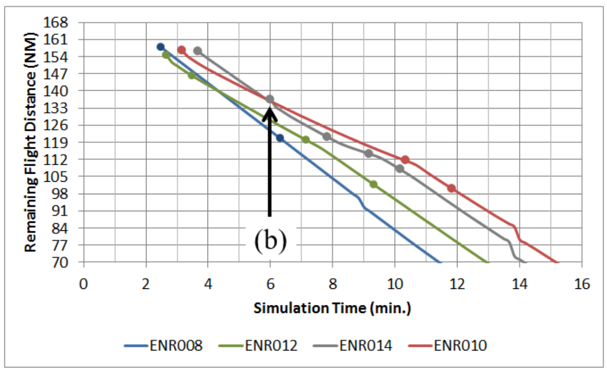

Fig.10 Process of In-Trail Spacing (Process-B)
(adapted from [9])

TRACEs of Fig. 10 also indicate the fact that it took longer time to stabilize the separation between ENR014 and ENR010 in Process-B. In addition, the position of the rearmost aircraft in Process-B (ENR010) was closer to the ADDUM point as compared to that of Process-A (ENR014), which can cause closer separation between ENR010 and other leading aircraft in Process-B. As described above, Process-B apparently requires more complex procedures to establish in-trail separations than Process-A.

Through the analysis described here, two types of ATC processes of in-trail spacing have been visualized. In addition, the analysis has successfully revealed the performance differences of the ATC processes and their probable causal factors. These facts imply the possible usefulness of COMPASi as a supporting tool of controllers' training.

5 Discussions

In the previous section, an example of the visualization and analysis of ATC process has been presented. As ATC services are provided in the trade-offs of multiple goals, *e.g.*, safety, efficiency, and expeditiousness, in varied and changing situations, it is impossible to make fixed procedures and manuals prescribing how to achieve the goals. In order to realize further effective training for controllers worked in such intractable conditions, not only the outcomes but also the processes of ATC tasks need to be carefully evaluated. The reason is that the skills of selecting appropriate working processes are essential for maintaining safe and efficient execution of tasks and also for regulating controllers' workload in dynamic situations. This kind of process-oriented training approach might be useful for enhancing resilience of plant personnel. For the process-oriented operators training, the development of task indexes and visualization methods for describing their working processes are required.

At present, our research described in preceding sections focuses on the visualization of technical aspects of controllers' working processes. However, non-technical aspects of operations, *e.g.*, communication, teamwork, and workload management, are also indispensable for assuring the appropriateness of adaptive and resilient responses. As noted in Section 1, the operations of nuclear power plants in prepared situations are performed strictly following prescribed procedures and manuals. Assuming those operation methods, plant personnel are highly trained and operational organizations and systems are well-designed. That means that a resilient response of an operator beyond prescribed procedures and manuals might lead to unintended mismatches in the operational organizations and systems and might cause significant human errors.

In order to prevent such adverse outcomes of resilient responses, knowledge and skills of plant personnel for effective communication and information sharing even in unprepared situations are definitely necessary. The design of operational organization and systems needs to be reconsidered whether they are tolerant to non-normal information flow and ad hoc responses. In short, organizational and systemic readiness is also required so that the resilient responses of plant personnel function for the purpose of maintaining safety and avoiding disasters.

6 Concluding remarks

For reference in considering needs and enhancements of the training of nuclear power plant personnel, this paper has introduced research on the visualization of Air Traffic Control (ATC) processes toward supporting controllers' training. Based on perspectives and experience obtained through the research, possible suggestions for enhancing the training programs of plant personnel has been discussed. The authors believe that this kind of information sharing of safety approaches and activities across industrial domains can significantly contribute to achieve the higher level of safety in modern complex systems. For preventing tragic accidents, we together should have the attitude to search for sharable lessons and applicable approaches in the safety activities of other domains, in spite of the attitude of searching for differences and reasons for the inapplicability.

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