Nuclear Plant Control Room Operator Modeling Within the ADS-IDAC, Version 2, Dynamic PRA Environment: Part 2 - Modeling Capabilities and Application Examples

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Abstract: Dynamic simulation-based approaches for probabilistic risk assessment (PRA) offer several key advantages over traditional “static” techniques such as traditional event tree-fault tree based methods. For example, dynamic simulation approaches can more realistically represent event sequence and timing, provide a better representation of thermal hydraulic success criteria, and permit more detailed modeling of operator response. Version 2.0 of the Accident Dynamics Simulator paired with the Information, Decision, and Action cognitive model in a Crew context (ADS-IDAC) is one such dynamic method that shows promise for supporting nuclear power plant PRAs and other risk-informed applications. By linking a realistic nuclear plant thermal-hydraulic model with a crew behavior model, ADS-IDAC creates a rich simulation environment. The crew behavior model describes the operators’ preferences and tendencies, knowledge, and situation-response rules. ADS-IDAC generates a discrete dynamic event tree (DDET) by applying simple branching rules that reflect variations in crew responses to plant events and system status changes. Branches can be generated to simulate a variety of operator behaviors, including procedure execution speed and adherence, evolving situational assessments, and variations in plant control preferences. This is the second of two papers in this volume and describes the dynamic modeling capabilities supported by the ADS-IDAC Version 2.0 simulation platform and provides examples of their application.

Keywords: Dynamic PRA, performance influencing factors, human reliability analysis

1 Introduction

The Accident Dynamics Simulator with the Information, Decision, and Action in a Crew context cognitive model (ADS-IDAC) provides a means to explicitly model the dynamics and feedback of nuclear systems while capturing the cognitive behavior and limitations of operators performing within a crew environment. The ADS-IDAC environment couples a thermal-hydraulic model with an operations crew cognitive model to permit the dynamic simulation of operator performance during NPP events. ADS-IDAC generates a discrete dynamic event tree (DDET) using simplified branching rules to model variations in crew responses. Branching events may include hardware failures; operator decisions or actions; and stochastic timing variabilities. IDAC decomposes the operator’s cognitive flow into three main process: information processing, decision-making, and action execution [1]. The crew is modeled as a team of individuals working on different assigned tasks and communicating with one another. The individuals differ by the content of their memory, by their mental state, and by the goals and strategies they employ. While the domain of applicability of IDAC is currently constrained to environments characterized by high levels of training and explicit requirements to follow procedures [2], this tool is capable of
providing useful insights across a range of nuclear power plant human performance issues.

This is the second of two papers in this volume and describes the dynamic modeling capabilities supported by the ADS-IDAC Version 2.0 simulation platform and provides examples of their application. The first paper provides an overview of the ADS-IDAC Version 2.0 simulation platform and a description the cognitive foundations underpinning the operator human performance model. Section 2 of this paper describes the dynamic capabilities of ADS-IDAC, Version 2.0, including the implementation of dynamic performance influencing factors and modeling variations in crew and plant response using dynamic branching capabilities. Section 3 provides an example application that highlights the dynamic information processing and procedure execution capabilities of ADS-IDAC.

2 ADS-IDAC, Version 2.0, Scenario Generation Capabilities

ADS-IDAC simulation generates a dynamic event tree (DDET) of the set of accident scenarios by activating branching points when certain conditions are met. Each branching point includes two or more individual event branches, each of which represents distinct combinations of system and operator states. Collectively, the branching points describe the topology of a DDET associated with an initiating event. A specific accident sequence is defined by the unique path through the DDET branching points from the initiating event to an end state. The generation of branching points is controlled by a set of general rules that define the specific activation conditions for a branching point. Although the branching rules are predefined, the creation of branching points depends on the dynamic behavior of the reactor plant and operator decision-making models. Consequently, a simulation approach is needed to determine the branching points that are generated along a specific accident sequence trajectory.

2.1 Dynamic Branching Capabilities

The ADS-IDAC simulation allows exploration of the impact of component failures and operator behaviors on plant safety. The DDET is constructed by allowing changes in plant and operator states at discrete points in time. Plant state changes include component actuations and failures while operator state changes may include decisions and interactions with plant hardware. A main limitation of this approach is that the computational effort needed to obtain a solution exponentially grows as the number of modeled component and operator states increases. This exponential growth is known as sequence explosion and can limit the practicality of simulation approaches.

During an ADS-IDAC simulation, a discrete dynamic event tree is constructed using a set of predefined branching events. These branching events represent variations in plant hardware and crew responses to plant events. The ADS-IDAC scheduler currently supports branching options for the following:

- Operator Preferences - Branches can be generated to represent various operator behaviors including a preference for the use of memorized information (rather than verification of parameter values and component states based on control panel readings), tendency to deviate from procedures and rely on actions based on the operator’s knowledge and experience of the reactor plant (i.e., use of knowledge-based actions), and information perception biasing.

- Decision Making - The ADS-IDAC decision-making process includes the ability to generate branching events for several key processes. These processes include goal and strategy selection and the activation of mental beliefs.
• Action Execution - Branches can be generated to represent the activation and activation timing of rule and skill-based actions, including the frequency of activation for repetitive control actions. Branching rules can also be used to reflect the time required to execute an action, variations in control inputs, and inadvertent omission of procedure steps.

• Hardware Failure and Recovery - This branching rule generates failure and success branches when component operation is demanded. If the operator attempts to restart failed equipment, branches representing component recovery and permanent failure are generated.

The unique trajectory through a set of branching events defines an accident sequence. By simulating a variety of branching configurations, ADS-IDAC can support an integrated assessment of the impact of hardware failures and operator decisions and actions on plant safety. Previous research efforts have demonstrated that ADS-IDAC is capable of simulating complex operator behaviors and equipment failures using a relatively small set of branching rules [3].

2.2 Performance Influencing Factor Models

ADS-IDAC employs both static and dynamic performance influencing factors (PIFs) to influence and shape operator behavior. As the name suggests, static PIFs are constant parameters intended to represent the fixed environmental and organizational factors that affect crew behavior. Conversely, dynamic PIFs reflect transient conditions and model variations in the operator’s mental state during a scenario. The IDAC model includes fifty performance influencing factors (PIFs) which can be used to influence operator behavior [4]. A focus of the development of ADS-IDAC, Version 2.0, was the implementation of several dynamic PIFs to demonstrate the capabilities available within a dynamic simulation environment. To this end, three dynamic PIFs were selected for implementation: time constraint loading, information loading, and system criticality.

2.2.1 Time Constraint Load

The time constraint load PIF represents the time available until a monitored plant parameter exceeds a critical threshold. Because operators will normally monitor more than one important parameter, the overall PIF value is based on the most time limiting parameter. The knowledge base profile for each operator includes data defining how the time constraint load PIF value is calculated, including a listing of plant parameters used to calculate the time constraint PIF value along with the associated critical threshold values. Typical parameters that may be factored into the calculation of the time constraint PIF include steam generator water levels, pressurizer water level, and reactor coolant system pressure.

In order to model the potential dependence between operating mode and critical parameter threshold values, two different threshold levels are used to calculate the PIF value – a normal operation threshold and an accident threshold. When the operator’s high level goal is maintaining normal operation, monitoring, or troubleshooting an abnormal condition, the normal operation threshold is used. These goals are associated with at-power operation; therefore, time limitations would be expected to be driven primarily by the desire to maintain normal operation by avoiding a reactor trip. If the operator switches to the goal of maintaining global safety margins (or if a reactor trip has occurred
with the troubleshooting goal active), the time constraint PIF value is based on the accident threshold.

The use of two different threshold values allows ADS-IDAC to capture an operator’s changing sensitivity to key parameters depending on the overall perceived plant condition. In general, the normal accident threshold is set to a level corresponding to reactor plant trip set points. The accident level threshold is normally set to a less restrictive value that is more indicative of the availability of a key safety function. For example, if a plant has an automatic reactor trip on low steam generator (SG) water level, an operator might focus on the time available until the reactor trip set point is reached during an uncontrolled decrease in SG level. However, once the reactor is tripped, the operator’s focus might shift to simply maintaining adequate decay heat removal capability from the steam generator - a function that can be often be performed with a much lower SG level.

Like all information processed by the operator model, the time constraint loading PIF value is based on information perceived by the operator rather than data obtained directly from the thermal-hydraulic model. Perceived data may differ from the actual parameter value in thermal-hydraulic model due to time lags in updating perceived data and any distortions introduced by perception filtering and biasing.

The first step in determining the time constraint loading PIF is to determine the time available until each time constrained parameter exceeds a critical threshold (Equation 1).

\[ t_{i, available} = \frac{P_i - P_{i,Threshold}}{\dot{P}_i} \]  

In Equation 2, \( t_{i, available} \) is the time until the value of parameter i (\( P_i \)) exceeds threshold value \( P_{i,Threshold} \) and \( \dot{P}_i \) is the rate of change of parameter \( P_i \). If an updated parameter value has not been perceived since the last PIF update, ADS-IDAC will extrapolate the parameter value based on the previously perceived parameter value and trend. To prevent this extrapolation process from artificially inducing an influence on operator behavior, when a parameter becomes the most time limiting factor, the operator’s parameter scan queue is checked to ensure the operator is actually monitoring the parameter. If the parameter is not being actively monitored by the scan queue, it is added to ensure that the limiting PIF value is based on perceived information rather than an extrapolation process.

An updated PIF value associated with each monitored parameter (\( PIF_{i,TimeConstraint} \)) is then obtained using the value of \( t_{i, available} \) (see Equation 2).

\[ PIF_{i,TimeConstraint} = 10 \left[ 1 - \left( \frac{t_{i, available} - t_{Lower}}{t_{Upper} - t_{Lower}} \right) \right] \]  

The tuning constants \( t_{Lower} \) and \( t_{Upper} \) are used to calibrate the PIF value to the desired operator characteristics. Equation 7a is applicable only when \( t_{i, available} \) is between \( t_{Lower} \) and \( t_{Upper} \). If the minimum time available exceeds \( t_{Upper} \), the time constraint PIF value is set to 0. If the minimum time available is less than \( t_{Lower} \), the PIF value is assumed to saturate at a value of 10.

In order to more realistically model dynamic changes in the time constraint PIF, the updated value of \( PIF_{i,TimeConstraint} \) is passed through a lag filter to simulate the gradual buildup and decay of stress associated with time constrained loading. This feature is intended to account for a decrease in induced time constraint loading once a parameter has passed a critical threshold, and the operator is unable to recover the parameter. In this case, the operator would likely focus on other critical parameters where mitigation actions may be more successful. The timing parameters can be adjusted by the analyst to match
desired crew characteristics. The overall value for the time constraint PIF value is the maximum value of PIF\textsubscript{TimeConstraint} for all monitored parameters.

### 2.2.2 Information Load

The information loading dynamic PIF represents the operator’s mental workload associated with the perception, processing, and communication of information. All information available from the nuclear plant thermal hydraulic model and crew communications must first pass through the operator’s perception filter before it can be memorized and used. Consequently, the flow rate of information through the perception filter provides a convenient measure of each operator’s information processing workload. The formula used to calculate the information load PIF is shown in Equation 3.

\[
PIF_{\text{Info Load}} = 10 \left( \frac{I_{\text{rate}} - \alpha}{\beta - \alpha} \right)
\]  

(3)

The variable \( I_{\text{rate}} \) represents the operator’s dynamic information processing rate and the calibration parameters \( \alpha \) and \( \beta \). The calibration parameters can be adjusted to reflect an individual operator’s information handling capabilities. Equation 8 is applicable only when \( I_{\text{rate}} \) is between \( \alpha \) and \( \beta \). If the information processing rate is less than \( \alpha \), the PIF value is set to 0. If the information processing rate is greater than \( \beta \), the information load PIF saturates to a value of 10.

### 2.2.3 Criticality of System Condition

The criticality of system condition PIF represents the operator’s perception of the level of degradation of key safety functions. This PIF is loosely based on the safety parameter display system used in U.S. nuclear plant control rooms [5]. The value of the system criticality PIF corresponds to the aggregate deviation of key safety parameters from a nominal value. Each operator profile identifies the parameters used to calculate this PIF, the threshold limits associated with each parameter, and the weighting factors used to aggregate the parameter contributions. Typical parameters used to calculate the system criticality PIF include reactor coolant system subcooling margin, wide range steam generator water levels, pressurizer water level, and reactor vessel water level. The contribution from each identified parameter to the overall criticality of system condition PIF value is denoted as the parameter criticality (PIF\textsubscript{Parameter Criticality}). Given a set of high and low threshold limits, the parameter criticality corresponds to the magnitude of the parameter’s deviation from a nominal “safe” condition (see Figure 1).

![Parameter Criticality](image-url)
As shown in Figure 1, the parameter criticality considers both high and low deviations from the nominal safe state. For example, a low level of reactor coolant system subcooling margin might indicate inadequate core cooling and an increased potential for core damage, while an excessive amount of subcooling might indicate an overcooling event and a potential pressurized thermal shock condition. The overall criticality of system condition PIF value is based on a weighted sum of the individual parameter criticality values (Equation 4).

\[
P_{\text{IF System Criticality}} = \sum \omega_i P_{\text{IF Parameter Criticality}}
\]

The \( \omega_i \) value in Equation 5 is the weighting factor for parameter \( i \). A higher value of the system criticality PIF indicates a more adverse overall plant condition. Additionally, the rate of change of the PIF value provides an indication if the overall plant health is improving or worsening.

### 2.2.4 Demonstration of Behavior of Dynamic PIFs

In order to demonstrate the behavior of the dynamic PIF factors, an example steam generator tube rupture (SGTR) scenario was analyzed. The appropriate response to a SGTR event requires several dynamic interactions with the reactor plant, including initiation of emergency core cooling, isolation of the ruptured steam generator, cool down and depressurization of the reactor coolant system, and termination of emergency core cooling. Each of these steps either initiates or terminates a significant trend in a key reactor plant parameter. The thermal-hydraulic response for a selection of key plant parameters is shown in Figure 2.

The dynamic plant response drives the behavior of the operator dynamic PIFs based on information perceived by the operators. The response of the time constraint loading, information loading, and system criticality PIF factors for the crew supervisor are shown in Figure 3.
As can be seen in the figure, the PIF response varies considerably over the accident scenario and reflects both the plant dynamics and the operator’s information perception. Of particular note is the ability of the time constraint loading PIF to mirror to dynamically reflect shifts in the operator focus during the event by transitioning between pressurizer water level, steam generator water level, and RCS pressure during the scenario. Similarly, the information loading PIF varies in response to real operator activity and plant conditions (e.g., peaks in information loading following the reactor trip and isolation of the ruptured SG). Finally, the system criticality PIF provides an indication of the operator’s perception of overall plant degradation, increasing as key parameters degrade and then leveling off and decreasing as emergency procedure actions stabilize the plant condition.

Collectively, these dynamic PIFs provide extremely rich contextual information that not only reflects the operator’s unique characteristics, but also can reflect the evolving context of an event.

3 Application Example – Skipping Procedure Steps

Procedures in ADS-IDAC follow a standard three part format consisting of an action, one or more conditions that should result from the action, and contingency actions that should be performed if the expected conditions are not met. This is consistent with a standard “action,” “action expectation,” and “response not obtained” format commonly used at some nuclear plants. An important aspect of this modeling approach is that ADS-IDAC is capable of capturing not only the content, but also the structural format of the plant procedures. Because procedures are structured such that the contingency actions are only performed if the action expectations are not met, the expectations occasionally use unusual phrasing. For example, an expectation intended to verify that the steam generators are intact might be worded “no steam generator pressure decreasing in an uncontrolled manner.” The interpretation of this condition would likely be influenced by
the operator’s biases and their situational assessment. ADS-IDAC is capable of representing these types of complex action expectations.

ADS-IDAC supports the modeling of omission of certain procedure actions in order to model step-skipping behavior. The likelihood of skipping a procedure step is calculated by adjusting a base probability value by dynamic and static multipliers. These multipliers reflect procedural characteristics, the relevance of the action to the operator’s situational assessment, and the state of performance influencing factors. In ADS-IDAC, Version 2, this capability is used to gain insights into the relative tendency of operators to omit a specific procedure step, rather than quantifying a human error probability. While this approach does not include all of the cognitive elements normally used by modern human reliability analysis methods, this example is intended to illustrate how contextual information from a simulation-based approach can be integrated into a human performance assessment.

3.1 Static Characteristics

Static characteristics refer to the properties of the procedure and do not change during the accident scenario. The static factors considered are procedure type, step objectives, and step complexity. The following taxonomy is used to assign values for the static factors:

- **The procedure type** is used to reflect the expected level of formality used by the crew when executing the procedure of interest. Consistent with quality assurance program guidelines in the US [6], plant operators are expected to specify the manner in which procedures are to be executed. This is expected to vary with the type of procedure with routine procedural actions that are frequently repeated generally requiring less formal requirements for procedure usage than procedures covering infrequent or complex tasks. Six procedure types are considered and each can be assigned a unique factor: normal operating, alarm response, abnormal, emergency optimal recovery guidelines, emergency functional recovery guidelines, and mental (skill of the craft) procedures. Operators are expected to be more likely to skip a procedure step when less formal procedure usage rules are used.

- **The step objective** is used to identify the alignment of the task addressed by the step with the overall objectives of the procedure. Steps that clearly accomplish tasks aligned with the high level objectives of a procedure are expected to be less likely to be skipped than steps that perform monitoring or verification activities. Five step objective categories are currently used in ADS-IDAC: monitoring, prerequisite task, verification, objective-related, and diagnosis-related steps. Monitoring steps require the operator to periodically check the value of a parameter or condition while verification steps require the operator to ensure that an expected condition exists. Prerequisite steps support later actions but are not directly associated with the high level goals of the procedure. Objective-related steps are directly associated with the high level goals of the procedure. Diagnosis steps require the operators to assess the plant state and possibly transfer to a new procedure path. Similar to the procedure type, a unique static factor can be assigned to each type of step objective.

- **The complexity of the procedure step** is also considered a static factor. Complexity can refer to the step structure, the type of action, and the presence of actions inside and outside of the control room. Similar to the static procedural factors, the static step complexity factor ranges from 1 to 10, with a higher value reflecting a greater tendency for action skipping. Based on research that indicates steps with
intermediate complexity may have the lower adherence that simpler or more complex steps [7], this factor reflects the likelihood of adherence due to step complexity rather than the actual step complexity. As procedure steps are coded into the operator knowledge base, the characteristics of each step are reviewed and static factors are assigned. The three static factors (procedure type, step objective, and complexity) are multiplied together to provide an overall static factor \( f_{\text{static}} \) for step-skipping.

### 3.2 Dynamic Characteristics

Two types of dynamic characteristics are used to adjust the basic step-skipping probability: (1) the time constraint loading performance influencing factors, and (2) the relevance of the action to the operator’s situational assessment. Because high time pressure may influence an operator’s tendency to skip procedure steps, the time constraint loading performance influencing factor (PIF) is included in the step-skipping model. The relevance of an action to the operator’s situational assessment is determined by comparing the functions associated with the target component referenced by the step to perceived plant functional imbalances based on the output from the diagnostic engine. A relevance score, which varies from 0.1 to 10, is then calculated for each step. A relevance score of 0.1 is associated with a procedural action that directly relates to a perceived plant functional imbalance such as manually scramming the plant if the reactor coolant system has excessive energy input. A relevance score of 10 is associated with an action that is irrelevant to perceived functional imbalances (e.g., checking containment pressure following an uncomplicated reactor trip). Actions that are not associated with a specific component (such as procedure transfers) are assigned a relevance factor of 1.0. Because the amount and accuracy of plant data perceived by the operator changes over time, the relevance factor is a dynamic quantity. Qualitatively, an operator with an accurate situational assessment and experiencing low time pressure will be less likely to skip pertinent actions, while an operator with a poor situational assessment may be more likely to skip important procedure steps. The relevance score for the step is multiplied by the time constraint load PIF to yield the overall dynamic factor \( f_{\text{dynamic}} \).

### 3.3 Implementation

Based loosely on the SPAR-H human reliability method [8], the step skipping probability is calculated from the static and dynamic step factors as follows (Equation 5):

\[
P_{\text{skip}} = \frac{P_{\text{base}} f_{\text{static}} f_{\text{dynamic}}}{P_{\text{base}} (f_{\text{static}} f_{\text{dynamic}} - 1) + 1}
\]

\( P_{\text{base}} \) is a base step-skipping probability and \( P_{\text{skip}} \) is the adjusted probability. The dynamic calculation of the step-skipping probability provides a number of advantages, including: (a) the ability to consider procedure type, step intent, and step complexity, (b) the influence of time pressure, and (c) the ability to link step-skipping tendencies to the operator situational assessment through the relevance factor.

To illustrate this approach for a realistic problem, the procedure step skipping model was applied to the complex loss of feedwater scenario used for a recent HRA empirical study [9]. The example scenario begins involves a complete loss of heat sink event and begins with a partial loss of condensate system flow with the reactor plant operating at 100% power. The resulting low condensate discharge pressure causes the main feedwater
pumps to trip on low suction pressure and results in a complete loss of feedwater. Following a successful reactor trip, both motor driven auxiliary feedwater pumps (MDAFPs) and the turbine driven auxiliary feedwater pumps (TDAFP) are assumed to fail. The operators are expected to diagnose that a complete loss of secondary makeup has occurred and initiate the functional recovery guideline for a loss of secondary heat sink. For this scenario, expected operator actions include tripping the reactor coolant pumps to minimize heat input into the reactor coolant system, depressurizing the steam generators (after successfully blocking the automatic low reactor pressure and high steam flow safety injection actuation signals), and aligning the condensate system to the steam generators before reaching the initiation criteria for feed and bleed cooling. Although steam generator depressurization can lead to successful recovery of feedwater flow, the high steam flow needed for depressurization reduces the steam generator water inventory faster and therefore reduces the time available until feed and bleed cooling must be initiated.

The results from the ADS-IDAC step-skipping model for this scenario are provided in Figure 4. Because the ADS-IDAC Version 2.0 step-skipping module has not been fully validated, only the relative likelihood of skipping procedural steps is shown in the figure. As can be seen, tripping the reactor coolant pumps and failing to block automatic safety injection actuation prior to steam generator depressurization were predicted as actions that may have a higher likelihood of being omitted by the crew. The failure to trip the reactor coolant pumps increases the heat input into the reactor plant and reduces the time available until feed and bleed cooling must be initiated. The failure to block safety injection may result in an inadvertent emergency core cooling system actuation which isolates the main feedwater system and complicates restoration of a feedwater source to the steam generators. Additionally, the need to continuously monitor SG pressure, combined with increased time pressure during SG depressurization, was predicted to result in a higher likelihood to inadequately control the depressurization. This may lead either to an excessive rate of depressurization (which may inadvertently actuate safety features) or an excessive amount of depressurization (which may delay restoration of feedwater).

Based on the results of crew observations for the LOFW scenarios [9], ADS-IDAC was able to either identify areas of significant crew to crew variability or qualitatively predict some crew behaviors. Although no crews skipped the procedure step directing tripping of all RCPs during the empirical study scenarios, there was wide variability in the time required to perform this action (with times between LOFW initiation and trip of the RCPs ranging from 7 minutes to 24 minutes). This observation provides some indication that the salience of tripping the RCPs during a loss of heat sink scenario may not have been consistent across all crews. Additionally, approximately half of the crews failed to block one or both of the automatic safety injection (SI) signals as required by procedure. Although the failure to block SI signals did not lead to a complicating safety injection signal for the affected crews, one crew did encounter issues monitoring and controlling SG depressurization and actuated an automatic SI signal due to a high differential pressure between steam lines. Based on these results, ADS-IDAC shows promise in supporting the identification of crew actions that either constitute failure events or may establish an error forcing context. It should be noted that this application was a simple feasibility study to demonstrate how dynamic approach could better inform HRA studies; additional research is needed to fully calibrate and validate this model for this type of application.
4 Conclusions

Recent additions to the ADS-IDAC simulation model have dramatically improved its ability to realistically represent operator knowledge, skills, and problem-solving styles. The recent implementation of dynamic PIFs reinforces the man-machine feedback loop and strengthens the transient modeling capabilities of ADS-IDAC. The recent implementation of a plant functional decomposition and diagnostic engine strengthens the ability to model knowledge based actions and procedure step skipping in ADS-IDAC. Taken together, these factors improve the ability of ADS-IDAC to model dependencies among operator behaviors such as skipping steps, selection of problem solving strategies, and information gathering. These improvements support the eventual application of ADS-IDAC to serve as a tool to support identification of nuclear plant operator cognitive errors, such as certain errors of commission.

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References


For Kevin Coyne’s biography, please see page 703 of this issue.

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