Identifying safety strategies for on-farm grain bins using risk analysis

Raymond S. Avery
University of Arkansas, Fayetteville

Dylan P. Carpenter
University of Arkansas, Fayetteville

Thomas A. Costello
University of Arkansas, Fayetteville

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Raymond S. Avery*, Dylan P. Carpenter§, and Thomas A. Costello†

ABSTRACT

The potential for grain bin accidents exists each year on Arkansas farms and farms across the nation. The trend toward increasing utilization of on-farm grain drying and storage could lead to an increase in grain bin accidents. The sharp contrast between a safe, efficient operation and one that leads to injury or death can be represented as sets of farmer-decisions and subsequent chance events. A model was constructed to define the risk associated with grain bin entry and in-bin activity so that safety interventions could be identified and implemented to reduce the probability of injury and death. A survey was distributed to Arkansas grain farmers to gather data on the level of safety education, storage techniques, operations management, and other parameters. The data collected from the survey provided quantitative input of many of the model's probability-distribution functions. Using a fault tree (with parallel modes of failure) in conjunction with a Monte Carlo simulation technique, we evaluated six safety intervention strategies and identified the one with the greatest potential for reducing the risk of serous injury or death. As part of senior design in biological engineering, plans are underway to design and test a probe that can locate and break bridged grain (a common risk factor in grain bin management) while working outside the bin on the ground.

* Raymond S. Avery will graduate in May 2003 with a degree in biological engineering.

§ Dylan P. Carpenter will graduate in December 2002 with a degree in biological engineering.

† Thomas A. Costello, faculty sponsor, is an associate professor in the Department of Biological Engineering.

MEET THE STUDENT-AUTHORS
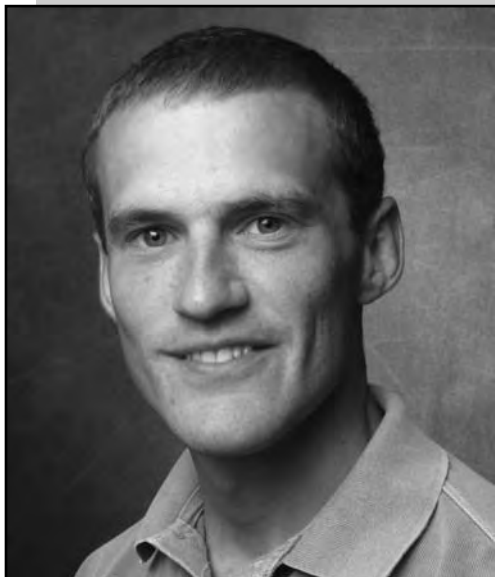
Ray Avery

I am a senior from Paris, Ark., majoring in biological engineering and plan to graduate in May 2003. I was a member of the 3rd place team at the 2001 AGCO national student design competition for our design of aeroponic growth chambers. I am a member of the American Society of Agricultural Engineers (ASAE) and am currently working with researchers to fabricate small mobile wind tunnels for studying ammonia volatilization. I chose this design project because of the long history of safety issues associated with grain bins on small farms.
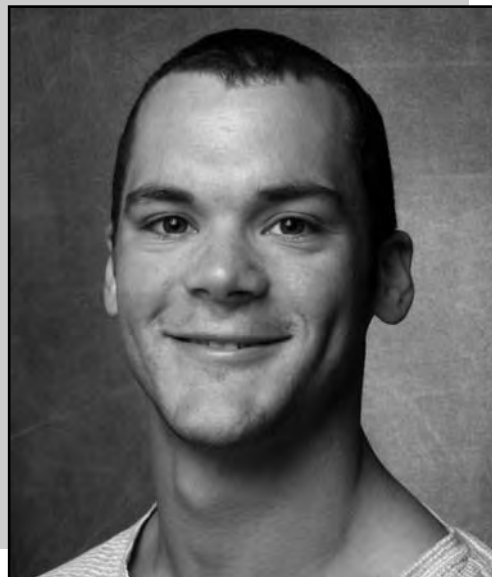
Dylan Carpenter

I was raised in Waldenburg, Ark., and graduated valedictorian from Weiner High School. I worked on the family farm managing crops and live fish. I am now a senior in biological engineering and a recipient of the Chancellor's Scholarship, Xzin McNeal Scholarship, and J.R. Riggs Scholarship. My plans include a future in medicine. I am an ambassador for biological engineering and an active member in ASAE, golden key, and alpha epsilon. Undergraduate research in proteomic analysis of thermozymes has stimulated my interest in the application of genomic and proteomic information to improve human health and well-being.

INTRODUCTION

Commercial grain storage facilities are bound by OSHA regulations, which provide safety standards such as those for confined space entry (OSHA, 1996). However, farms consisting of less than 10 employees are exempt from OSHA guidelines. Because on-farm grain storage is being increasingly utilized, safety concerns are mounting due to common misconceptions about the hazards of grain entrapment and suffocation. Research shows that many operators are unaware of how grain flows from a bin under different conditions (Loewer and Loewer, 1993). When a metal storage bin is emptied using a bottom-unloading auger, the grain at the top is removed before the grain at the bottom (Loewer and Loewer, 1993). Once grain begins to flow, it expresses the physical properties of a fluid; however, at rest the grains are a complex matrix of individual solid particles. Farmers who fail to understand the nature of flowing grain may unwittingly put themselves or others in dangerous situations. It takes approximately 3 seconds to remove the volume of grain displaced by a 73-kg (160-lb)

person using a 20-cm (8-in) auger in a typical on-farm grain handling system (Kingman et al. 2001). Grain bin operators tend to think that they could free themselves from grain engulfment by their own strength. However, it would be impossible or debilitating to produce and exert the force required to extract a person from total submersion (Schwab, 1994). In order to prevent suffocation due to grain entrapment, the most hazardous conditions and sequences of farmer decisions, actions and outcomes need to be identified and analyzed. With this knowledge, engineering and expert management solutions can be developed.

In the engineering design process, probability uncertainties must be justified through a logically sound method. Risk assessment involves the quantification of potential failure modes in an operation and the failure types, likelihood, and consequences (Wang and Rousch, 2000). Risk assessment and ultimately risk management can be used to optimize the design process by addressing and reducing the amount of uncertainty and potential for catastrophic failure. In order to design grain bin safety devices, we need to properly identify, understand, and quantify the probability of various modes of failure causing grain-bin accidents.

While working inside grain bins, four potential hazards may exist.

1) A significant danger occurs when the farmer-operator goes into a bin while the unloading auger is in operation and grain is flowing. Flowing grain exhibits fluid properties that may engulf a worker before escape is possible. Proper safety measures include locking the auger control in the off position before bin entry. Educational efforts have been targeted at clearly describing this hazard so that farmers will avoid this dangerous situation (Loewer and Loewer 1993).

2) Grain in poor condition (e.g., moist, moldy or decomposing grain) may create a bridge that alters or stops the flow of grain during unloading. The bridge and subsequent partial unloading may create a cavity in the grain mass. If the bridge collapses suddenly, grain will flow to fill the void below. An operator working at the grain mass surface could be rapidly engulfed and covered by an avalanche of grain (Kingman et al. 2001). The intrinsically safe method would be to break the bridge or obstruction without entering the bin (an external method) using a specialized device (such as an Archmaster from Mole-Master Services Co., Marietta, OH) that are used in commercial grain facilities. If bin entrance is necessary, a harness and lifeline should be used with assistants at the bin entrance and on the ground (as required by OSHA for commercial operations, OSHA, 1996). Currently, most farmers do not have access to such safety devices and would probably not seek and employ additional workers for assistance.

3) Once grain unloading is nearly complete and residual grain is moved using the horizontal sweep auger at the bottom of the bin, vertical crusting of residual grain along the bin wall may become a hazard. Tremendous pressure on the grain during storage and poor physical quality of the grain can produce a wall of crusted grain with a slope much greater than the angle of repose (Loewer and Loewer, 1993). If the farmer attempts to remove the residual crust while working from the bin floor, the vertical wall of grain may collapse and cover the worker (Loewer and Loewer, 1993). Proper grain harvesting and storage techniques (cleaning, drying, and aeration) are needed to prevent crusting. When it does occur, workers should attempt to dislodge the grain by operating from above (using a harness and lifeline).

4) Kingman et al. (2001) showed that nearly 40% of the documented grain suffocations in the U.S. occurred in children under age 15. Therefore, safety education could be used to reduce these accidents by changing the way farm parents supervise their children (i.e., not allowing children to play around grain bins and grain wagons).

The objective of this project was to determine distinct decision progressions and failures that lead to accidents and to identify safety interventions that will have the greatest benefit in terms of reducing the likelihood of serious injury or death associated with on-farm grain storage. The success of any proposed safety intervention will be determined not only by the effectiveness of the design in providing logistical help to the farmer to avoid entrapment and suffocation, but also by the likelihood that the method will be available and implemented. Hence, economics, convenience and education must be considered since safety is essentially a voluntary activity for small operators.

MATERIALS AND METHODS

A hazard analysis was used to define the possible reasons for bin entry that may lead to entrapment. We defined the greatest hazards to be: 1) collapse of a void below bridged grain following flow interruption; 2) engulfment in flowing grain during bin inspection while unloading; 3) children playing in bins; and 4) collapse of vertically crusted grain. A risk assessment was performed to better understand the sequence of events that lead to the 4 hazards listed above. This process explicitly showed how potentially unsafe actions usually avoid injury or death because of a fortuitous (and actually highly likely) sequence of events. However, given a large
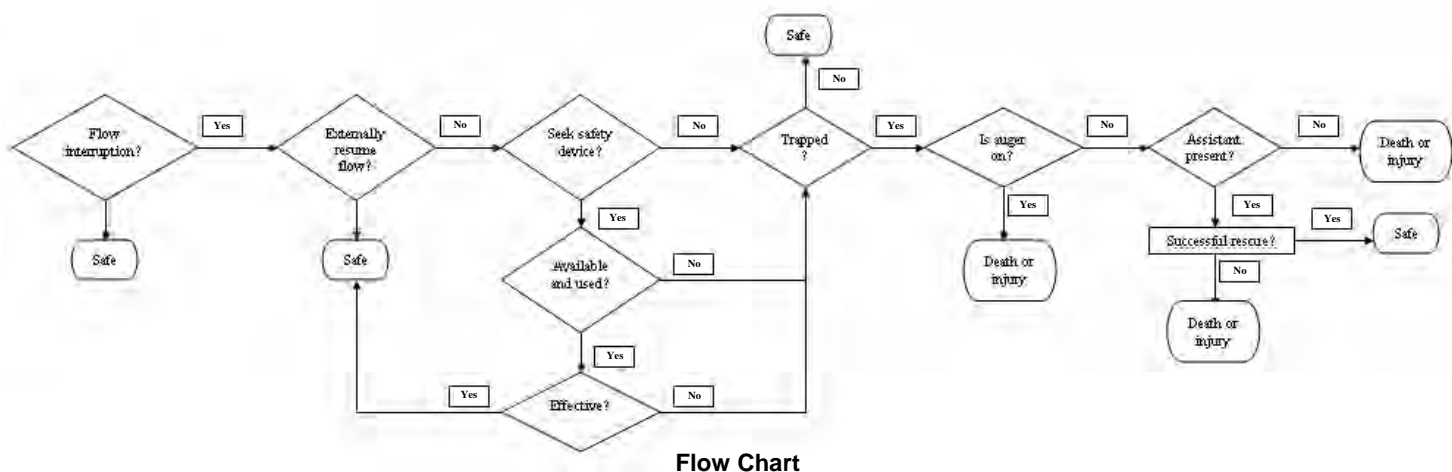
Flow Chart

Fig. 1. Portion of the fault tree used in the risk assessment. An example of a parallel decision-process flow chart due to a flow interruption, which illustrates the farmer's problem-solving process that could result in injury/death or a safe outcome. For example, education could persuade a farmer to seek a safety device that resumes normal flow from outside the bin thereby preventing exposure to hazards directly linked to injury or fatality.

number of grain bin operations, eventually the fatal combination of events will occur. Our hypothesis is that a well-designed safety strategy could precisely place a roadblock that would prevent a fatal chain of events while operating within the farmer's logistical and economic constraints.

A fault tree (Fig. 1) was constructed using Precision Tree™ software (Palisade Corporation, Newfield, NY) to describe the parallel and sequential chance events and decision processes that contribute to injury and death from grain bin operations. The fault tree relies on a parallel system to determine the probability of death from each of the hazard modes. With the parallel system approach, the system fails when all of the components fail in any parallel mode (Haimes, 1989). The probability of death per year per farm was found by estimating the number of times a hazard occurs (the exposure) and by independently examining each mode of failure to estimate the probability of failure.

A survey was composed and distributed through county extension agents to on-farm storage operators in each of the top 10 grain-producing counties in Arkansas. The survey covered relevant information about each farm such as the number of grain bins, cropland area devoted to grain crops, fraction of harvested grain stored on-farm, perceptions of the likelihood of accidents, frequency of routine events, frequency of problem events, participation in education, opinions on factors that cause grain bridging, problem-solving decisions, and attitudes on the use of safety devices.

The survey helped define a base model of the existing hazard exposures and decision-making processes of farmers in the region prior to any intervention. For example, responses to a group of problem-solving questions were used to define a probability distribution for the likelihood of a farmer entering a bin to break a bridge. The probability distribution function was defined by estimating minimum, most likely (mean), and maximum values of a triangle distribution function in @Risk software (Palisade Corp., Newfield, NY). The triangle distribution was simple and robust and allowed the farmers' expert opinions to be directly used as input-probability density functions in the model. A Monte Carlo simulation then randomly chose values from each of the 113 independent model input distributions in the decision tree and performed 100,000 iterations. This simulation technique provided results to quantify the probability of injury or death.

A sensitivity analysis was performed to identify those key parameters which had the greatest impact on the probability of injury or death. Based upon the sensitivity analysis and insight gained through the process of constructing the fault tree, six potential safety interventions were proposed: 1) Educational safety program, 2) External probe bridge breaker, 3) Automated auger locking system, 4) Internal cable bridge breaker, 5) Safety harness and self-locking lifeline, and 6) Combination of (1) and (2). For each intervention (described further in the next section), the distribution functions in the model were modified to represent an estimated change in the

farmer's decisions and actions associated with that intervention. The Monte Carlo simulations for each separate intervention were then compared to the base model to compute the estimated mortality reduction (Table 1).

RESULTS AND DISCUSSION

Of the approximately 130 surveys sent, 69 farmers responded (53% response rate). The average farm produced 930, 1400 and 420 acres of rice, soybeans and wheat, respectively. On-farm grain storage (average of 10.4 bins per farm) was utilized for 73, 24, and 14% of the harvested rice, soybeans and wheat, respectively. The farmers surveyed believed that collapsing bridges (64% of respondents) and auger engulfments (62% of respondents) were two causes of accidents most likely to occur (Fig. 2); however, survey results showed that these accidents are considered rare. To avoid these rare catastrophes at least 50% of the respondents stated that they would have a helper present, turn off the equipment, and try to break a bridge from outside the bin before entering the bin (Fig. 3). Farmer's also expressed in the survey (data not shown) a willingness to participate in educational programs, which indicates potential for safety program development. Survey results suggested that an external bridge breaking device coupled with safety education might be the optimal safety intervention.

The risk assessment model (coupled with realistic inputs based on the survey) is an engineering tool that was used to optimize the final design solution. The survey facilitated construction of a model that represented the personal knowledge, practices, and decision-making processes of farmers in the grain-producing region. This is critical since these factors vary geographically due to differences in climate, soils, crop selection, farm practices, education, and culture. For example, national statistics indicated that the majority of grain suffocations and injuries occur with children; however, our survey results suggested that the majority of farmers in the Arkansas sample believed that children are less endangered. Approximately 70% of responses agreed with a statement that children "never" climb on, look at or play in or near the bin. The deviation between the survey results and the actual statistics represents a need for education and precise tracking of farm accidents.

From the base model Monte Carlo simulation, the mean predicted value of deaths resulting from grain bin entry in Arkansas was 0.92 per year (Table 1). The actual number of deaths related to grain bin entry in Arkansas is difficult to determine, but is estimated to be one death every two to three years (Huitink, 2002). There is uncertainty associated with the input probability distribution functions (particularly those that define numbers of entrapments and deaths associated with
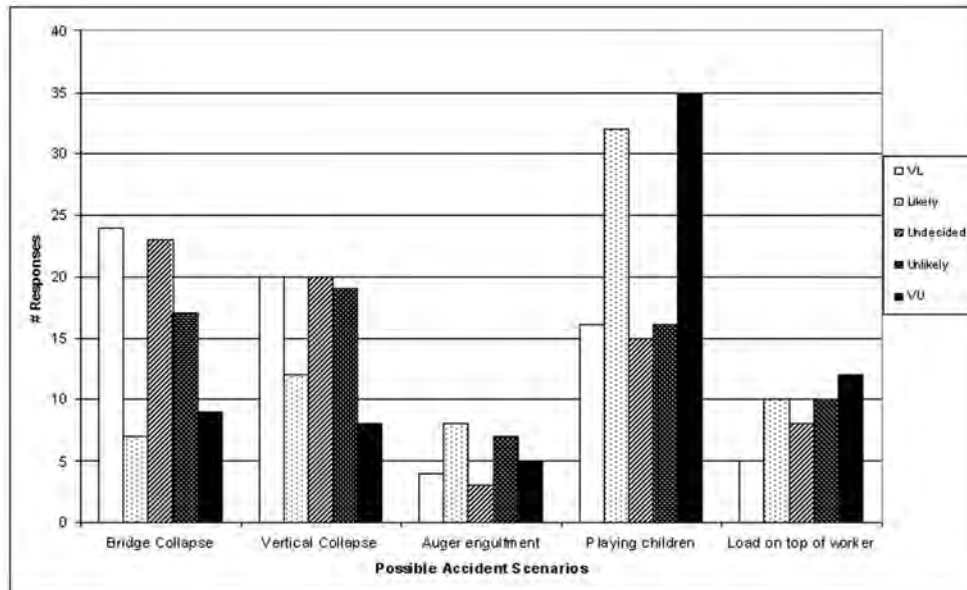
Fig. 2. Likelihood of accidents. Survey responses for farmers' estimates of the likelihood that a person could be trapped, injured or killed by an accident involving (1) collapse of bridged grain, (2) collapse of vertically crusted grain, (3) engulfment in flowing grain while the unloading auger is running, (4) children that entered bins to play, (5) grain loaded on top of a person inside the bin.
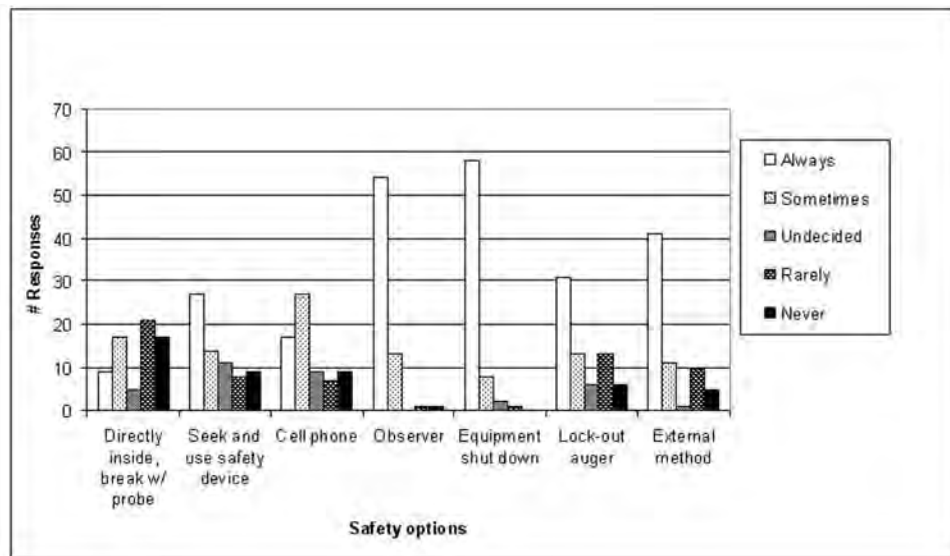
Fig. 3. Problem-solving decisions. Survey responses for farmer's actions when grain quits flowing during unloading and bridging is suspected.

Table 1. Results of safety intervention analysis in on-farm grain storage showing reduction in predicted mortality associated with six safety interventions.

Intervention	Hazard	Affected nodes	Triangle distribution parameters (max, mean, min)		Mortality (deaths per year in Arkansas)		
			base model	intervention model	Base	Intervention	Reduction
Education	Bridge	Seek safety device	(0.068, 0.41, 0.99)	(0.068, 0.93, 0.99)	0.92	0.89	3.3%
		Auger off	(0.068, 0.89, 0.99)	(0.062, 0.88,0 .99)			
		Observer	(.068, .88, .99)	(.062, .88, .99)			
	Children	Child attracted	(0.15,0.25,0.3)	(0.1,0.175,0.25)			
		Child enter bin	(0.05,0.1,0.15)	(0,0.05,0.1)			
	Vertical crust	Safe distance	(0.2,0.6,0.7)	(.02,0.3,0.4)			
External probe bridge breaker	Bridge	Break from outside (large cavity)	(0.1,0.25,0.35)	(0.8,0.9,1)	0.92	0.37	60%
		Break from outside (small cavity)	(0.65,0.75,0.85)	(0.8,0.9,1)			
		Device available and used	(0,0.05,0.1)	(0.2,0.2045,0.4)			
Auger-Lock	All	Auger off	(0,0.88, 0.99)	(0.93, 0.96, 0.99)	0.92	0.92	0.94%
	All	Device available and used	(0,0.05,0.1)	(0.1,0.28,0.38)			
Internal cable bridge breaker	Bridge	Device available and used	(0,0.05,0.1)	(0,0.06,0.1)	0.92	0.87	6.1%
	Bridge	Break from outside	(0.1,0.25,0.35)	(0.2,0.3,0.4)			
Harness/lifeline	Bridge	Trapped (break bridge)	(0,0,0.0002,0.005)	(0,0,0.0002,0.0005)	0.92	0.78	15%
		Trapped (no break)	(0,0,0.0018,0.005)	(0,0,0.00018,0.0005)			
	Vertical crust (tall/short)	Trapped (break safe distance, on grain)	(0,1E-5,5E-5)	(0,1E-6,5E-6)			
		Trapped (danger distance, on grain)	(7.5E-2,8.5E-2,9.5E-2)	(7.5E-3,8.5E-3,9.5E-3)			
	Inspection	Trapped (structure)	(4E-4,5E-4,1.2E-3)	(4E-5,5E-5,1.2E-4)			
		Trapped (sampling)	(4E-4,5E-4,1.2E-3)	(4E-5,5E-5,1.2E-4)			
	All	Device available and used	(0,0.05,0.1)	(0.1,0.1925,0.3)			
Education & external		Combined			0.92	0.35	63%

each specific exposure) and biased survey results. Research is needed to understand and quantify entrapment and mortality probabilities. A wider survey base along with better regional statistics should be sought to increase the model's precision.

An optimized solution was found by comparing the mortality reduction of each intervention.

(1) Education reduced the mortality rate by only 3%. This may be an underestimate of the value of education. The base model was calibrated to farmer's survey responses, in which they reported that they utilize good safety practices, however, we suspect that in reality, short cuts are often taken. Education could help farmers recognize a potentially lethal situation and take safety precautions.

(2) The external-pole bridge breaker (EPBB), was envisioned as a device that would allow a farmer to break bridged grain from an external ground position. It reduced mortality rate by 60% because it affected the fault tree in one of the most sensitive nodes (and required no bin entry).

(3) Automatic auger-lock (to prevent auger operation while someone is in the bin) showed only a 1% reduction in mortality rate because getting trapped during routine unloading represented a small number of predicted fatalities.

(4) The internal cable bridge breaker was envisioned as a cable/winch system installed inside the bin (before loading) which could be retracted and pulled up through the grain surface and possible bridges if flow interruption occurred. It reduced mortality by only 6% because it was considered less effective than the EPBB (when it failed the farmer would resort to in-bin methods).

(5) The harness/lifeline lowered the probability of becoming trapped and resulted in a 15% mortality reduction. We predicted that it would be used less often than the EPBB due to cost and logistical factors. The harness/lifeline also involved bin entry.

(6) A combination of the external-pole bridge breaker and education resulted in a 63% mortality reduction. This was a slight improvement over EPBB alone because education increased the likelihood that a safety device would be used.

The combination of EPBB and education was identified as a preliminary design concept for an engineering solution to the grain bin safety problem. A prototype of the external bridge-breaking probe, with a vibrating head and inflatable bladder that will allow a farmer to reach and break bridged grain from an external location has been constructed and tested as part of our senior design project in biological engineering. Development of suggestions for safety education in Arkansas is under consideration as well.

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