TITLE: An Evaluation of Spindle-Shaft Seizure Accident Sequences for
the Schenck Dynamic Balancer

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**AN EVALUATION OF SPINDLE-SHAFT SEIZURE ACCIDENT SEQUENCES
FOR THE SCHENCK DYNAMIC BALANCING MACHINE**

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AN EVALUATION OF SPINDLE-SHAFT SEIZURE ACCIDENT SEQUENCES FOR THE SCHENCK DYNAMIC BALANCING MACHINE

Terry F. Bott and Stewart R. Fischer

EXECUTIVE SUMMARY

This study was conducted at the request of the US Department of Energy/Albuquerque Operations Office (USDOE/AL) Dynamic Balancer Project Team to develop a set of representative accident sequences initiated by rapid seizure of the spindle shaft of the Schenck dynamic balancing machine (DBM) used in the mass properties testing activities in Bay 12-60 at the Pantex Plant. This analysis had two primary purposes.

1. The development of a physically reasonable set of representative accident sequences initiated by rapid deceleration of the rotating assembly as a result of spindle-shaft seizure and ending when the reentry vehicle (RV) leaves the DBM
2. The identification of potential causes of spindle-shaft seizure resulting in rapid deceleration of the rotating assembly

At the direction of the USDOE/AL Dynamic Balancer Project Team, the scope of the effort was limited as follows.

1. The effort was to be entirely qualitative, focusing on the identification of representative accident scenarios given spindle-shaft seizure. No efforts were made to quantify basic events or to assess likelihoods or probabilities of accident sequences. Consequently, relative ranking of scenarios, developing importance measures, or assessing uncertainty was not possible.
2. The accident-sequence development extended only to the point where the RV either remains stable on the DBM or where the RV leaves the machine with translational and rotational motion.
3. No supporting deterministic analyses were performed to assess whether identified potential causes of spindle-shaft seizure were physically possible.
4. No investigation was conducted to evaluate past operating experience with the Schenck DBMs.

This study used the methods of probabilistic safety analysis to evaluate possible accident sequences involving a loss of control of the RV resulting from sudden seizure of the rotating spindle shaft during operation of the DBM in the mass properties Bay 12-60. These methods include fault-tree analysis, failure modes and effects analysis, cause-consequence analysis, and hazard assessment. A list of possible accident sequences was developed and potential causes were identified based on this evaluation. The results of the analysis can be summarized as follows.

- Shaft seizure may result from a number of causes, such as a severe load imbalance, failure of an axial bearing, failure of a radial bearing, failure of a bearing housing seal, or a primary shearing failure of the spindle shaft.
- A significant over-speed condition on the DBM at the time of accident initiation would increase the probability of loss of control of the RV and exacerbate the consequences of the accident by increasing the energy of the RV when impacting a stationary object in the bay. The speed controls and protective features for the DBM appear to be highly redundant and diverse, and no obvious common cause could be identified.
- Improper attachment of the fixture containing the RV to the DBM or improper assembly of the fixture could significantly increase the probability of an accident if a spindle shaft seizure does occur. These conditions could result from human error in selection of bolts, improper installation of bolts, or wear/aging of equipment (including cracking of fixture welds or components). Although the bolt sets are redundant, a significant potential for common-cause faults that affect all the bolts in a set is present because of human error.

- If spindle shaft seizure does occur, several DBM accident conditions can result.
 - The fixture and RV remain attached to the DBM and are arrested in their motion.
 - The spindle shaft or all the shaft bolts completely shear, and the fixture/RV/face-plate system continues to rotate.
 - All the face-plate bolts shear and the unattached fixture continues to rotate.
 - All but one of the face-plate bolts shear, and the fixture begins to rotate about the surviving bolt.
 - The fixture structure fails, and the unattached RV (possibly along with some part of the fixture) continues to rotate.
- As a result of these DBM accident conditions, the subsequent RV motion can include the following.
 - The RV remains in the attached fixture and decelerates in a stable configuration because of friction with the fixture mountings.
 - The unattached fixture/RV/face-plate system continues to spin undergoing precessional motion but constrained in the angle of inclination by the decking and bearing plate of the DBM. The eventually RV comes to rest still in the fixture, which is more or less upright on the DBM.
 - The unattached fixture/RV system begins unconstrained precessional motion and "walks" off the DBM decking. The fixture/RV system falls to the bay floor still spinning and rolls or tumbles across the bay floor.
 - The fixture/RV system continues to rotate about a single face-plate bolt until the RV and fixture eventually come to rest, still attached to the single face-plate bolt
 - The fixture/RV system rotates about the single surviving bolt until it impacts the alignment pole.
 - The fixture/RV system rotates about the surviving bolt until the bolt breaks and the fixture/RV system flies off the DBM with both translational and rotational motion.
 - The RV is ejected from the fixture during precessional motion or rotation about a single face-plate bolt.

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Abstract

This study was conducted at the request of the USDOE/AL Dynamic Balancer Project Team to develop a set of representative accident sequences initiated by rapid seizure of the spindle shaft of the Schenck dynamic balancing machine used in the mass properties testing activities in Bay 12-60 at the Pantex Plant. In addition, the study identified potential causes of possible spindle-shaft seizure leading to a rapid deceleration of the rotating assembly. These accident sequences extend to the point that the reentry vehicle either remains in a stable condition on the balancing machine or leaves the machine with some translational and rotational motion. Fault-tree analysis was used to identify possible causes of spindle-shaft seizure, and failure modes and effects analysis identified the results of shearing of different machine components. Cause-consequence diagrams were used to help develop accident sequences resulting from the possible effects of spindle-shaft seizure. To make these accident sequences physically reasonable, the analysts used idealized models of the dynamics of rotating masses. Idealized physical modeling also was used to provide approximate values of accident parameters that lead to branching down different accident progression paths. The exacerbating conditions of balancing machine over-speed and improper assembly of the fixture to the face plate are also addressed.

1.0. INTRODUCTION

This report summarizes the results of an investigation of possible accident sequences arising from the sudden seizure of the hydraulic spindle of the Schenck dynamic balancing machine used at the Pantex Plant for balancing reentry vehicles (RVs). The analysis, which used risk assessment techniques, had two primary purposes.

1. The development of a physically reasonable set of representative accident sequences initiated by rapid deceleration of the rotating assembly because of spindle-shaft seizure and ending when the RV leaves the balancing machine
2. The identification of potential causes of spindle-shaft seizure resulting in rapid deceleration of the rotating assembly

At the direction of the USDOE/AL Dynamic Balancer Project Team, the scope of the effort was limited as follows.

1. The effort was to be entirely qualitative and focus on the identification of representative accident scenarios given spindle-shaft seizure. No efforts were made to quantify basic events or entire accident sequences to assess likelihoods or probabilities. Consequently, relative ranking of scenarios, developing importance measures, or assessing uncertainty was not possible.
2. The accident sequence development extended only to the point where the RV either remains stable on the balancer machine or leaves the machine with translational and rotational motion.
3. No supporting deterministic analyses were performed to assess whether identified potential causes of spindle-shaft seizure were physically possible.
4. No investigation was conducted to evaluate past operating experience with the dynamic balancer machines.

The analysis discussed here follows the cause-consequence analysis (CCA)¹ paradigm. In CCA, both causes and consequences of accident initiating events are developed systematically. The causes of initiating events are determined through deductive reasoning, typically using fault trees. The consequences of the initiating events are developed by inductive methods such as failure modes and effects analyses (FMEAs), event trees, or cause-consequence diagrams (CCDs). The inductive models of the accident sequences often include branch points representing failures of components or other events. The causes of branch-point events also may be developed using fault trees. In this study, fault trees, FMEAs, and CCDs are used both as logical aids in developing accident sequences and for graphical presentation of the results.

The analysis process used in this study is outlined schematically in Fig. 1. The dynamic balancing machine analysis began with the development of a high-level "RV Impact" fault tree. This fault tree was used to identify the range of accidents that could result in an RV impacting a stationary object while spinning on the balancing machine. This fault tree is shown in its entirety in Appendix A. Many of the cut sets of this fault tree include sudden deceleration of the rotating assembly, which is one potential outcome of hydraulic spindle-shaft seizure.

The causes of spindle-shaft seizure are developed in the "Spindle-Shaft Seizure" fault tree, which is presented in Appendix C. This fault tree uses results from the cut sets of the RV Impact fault tree as indicated by the connecting arrow in Fig. 1. The cut sets of the Spindle-Shaft Seizure fault tree are sequences of events that lead to shaft seizure. Possible consequences of spindle-shaft seizure are explored in the "Spindle Parts" FMEA, which examines the effects of shearing the spindle shaft, structural members of the fixture assembly, and the bolt sets that transmit rotational energy between the RV and the hydraulic spindle. This FMEA helps outline the beginning of the accident sequences resulting from shaft seizure.

The accident sequences resulting from failure of the shaft, bolt sets, or fixture were dependent on a general understanding of the physical phenomena that could occur when a rotating mass becomes unattached from the driving source for its rotation. An understanding of these phenomena was gained by developing idealized and simplified physical models of rotating bodies.² This model is represented by the "Physical Modeling" circle in Fig. 1. These models are presented in Appendices E through G. The models are not intended to give a detailed prediction of the motion of the fixture and RV, which is likely to be chaotic and extremely complex. They are intended to provide a simple physical basis for identifying possible accident progression paths based on the physically reasonable motions of the fixture and RV and to explore the regions in the problem parameter space that could lead to different accident sequences. These simple physical models were used to evaluate the implications of the fixture rotating about a single surviving face-plate bolt, the conditions under which RV ejection from the fixture might occur, and the probability of the fixture striking the alignment pole when rotating about a single bolt.

CCDs are used for a graphical representation of the "Causes," "Consequences," and "Accident-Sequence Models" boxes in Fig. 1.

The structure of the accident sequences is developed in the "Consequences" section of the CCD. The paths through the CCD are the accident sequences. The likelihood of taking different paths through the CCD can be explored by developing the branches at each operator in it. The concept and interpretation of a CCD are discussed in Appendix D. The consequence in this analysis is the condition of the RV when it either decelerates in a stable configuration on the balancing machine or leaves the balancing machine. There was no attempt to determine the ultimate fate of the RV. This study provides RV conditions that can be developed to determine weapon response when an RV that leaves the balancing machine reaches its final condition.

A simple ancillary fault tree was developed to explore the causes of improper bolt assembly. This condition could increase the likelihood of a shaft seizure resulting in RV impact accident sequences. A fault tree showing the different possible combinations of bolt conditions are developed in the "Bolt Shear" fault tree shown in Appendix B. Conditions leading to over-speed of the machine that also could lead to increased likelihood of shaft seizure and RV impact were addressed in a some detail in a report by Konkel (1997).

Fig. 1. Outline of the cause-consequence analysis process.

2.0. DYNAMIC BALANCING MACHINE DESCRIPTION

Many parts of the dynamic balancing machine will be referred to in this report. To aid the reader in visualizing which parts are being discussed, some simple pictures of the relevant portions of the balancing machine are included in this section. These pictures are based on information taken from several sources⁴⁻⁷ as well as personal inspection of the dynamic balancing machine in the mass properties bay and a partial machine disassembly. A simplified diagram of the machine with the positions of the components discussed in this study is shown in Fig. 2. This diagram shows the locations and interrelationships of the important components discussed in this report. Objects that are to be balanced are placed on the **face plate** of the machine. For Pantex operations, a fixture is needed to hold the RVs that are being balanced (the RV is shown as a triangle in the figure). This fixture typically is constructed in two parts, held together by a set of **fixture bolts**. The fixture is bolted to the face plate with a set of four to eight **face-plate bolts**. The face plate is directly driven by a drive belt. The drive belt is driven through

power train that includes the motor drive train, a bevel gearbox for speed reduction and direction change, and a DC shunt motor. The **hydraulic spindle** provides radial and axial alignment and stability for the face-plate spindle. The spindle also provides thrust support. The entire balancing machine is supported and stabilized by a heavy structure that includes a thick metal **bearing plate** beneath the face plate.

A color-coded close-up of the connection of the face plate to the spindle shaft is shown in Fig. 3. The important features to note in this figure are the limited clearance between the face-plate **extension** and the **bearing plate** and the **decking** (also called the shroud) shown in Fig. 3. The decking consists of plates of about 1/4-in.-thick aluminum attached to the balancing machine frame. The decking comes close to the edge of the face plate, but the extensions extend beyond the decking. Even limited tipping of the face plate will result in contact between its extensions and

Fig. 2. Simplified diagram of the dynamic balancing machine.

the decking underneath as well as the bearing plate on the top. The **shaft bolt** set that connects the spindle shaft to the face plate is located in a recess in the face-plate assembly; the eight bolts attach the face plate to the spindle shaft.

A simplified schematic of the spindle-shaft bearing is shown in Fig. 4 to help the reader follow the analysis. The redundancy in axial bearings is an important feature of the hydraulic spindle. The main axial bearing consists of a floating ring. The back-up axial bearing is a roller bearing. In addition to the axial bearings, two radial bearing are used to align the shaft, one near the top and one near the bottom of the bearing assembly. The bearing is sealed at either end with labyrinth-type seals filled with bearing grease.

A simplified schematic of the hydraulic oil system is shown in Fig. 5. Hydraulic oil is provided to the bearings by two pumps and sets of lines, one each for the radial and one each for the axial bearings. However, a common return line is used for all the hydraulic oil. The hydraulic oil system includes filters, relief valves, a chilled water cooler, emergency surge-capacity bladders pressurized by nitrogen, and control systems. All of these features were included in the fault trees developed in this analysis.

3.0. REENTRY VEHICLE IMPACT FAULT TREE

The accident sequences addressed in this study are a subset of the class "Impact of an RV on a Stationary Object During Balancing Machine Operation." A fault tree was used to help enumerate the members of this class of accidents and develop a logical model of how these accidents could occur. This fault tree places spindle-shaft seizure accident sequences in their proper context among other RV impact accidents. The RV impact fault tree is given in Appendix A. This fault tree is developed only to the point where the cause of RV impact can be identified. All RV impacts caused by spindle-shaft seizure leading to rapid deceleration were examined further using CCA.

Four main accident subclasses involving the impact of an RV on a stationary object during balancing machine operation were identified.

- Fixture breakup
- A rotating fixture striking a stationary object
- A fixture being ejected from the rotating balancing machine
- An RV being ejected from a rotating fixture.

Each of these accident subclasses is discussed below.

- **Fixture Breakup**

Fixture breakup occurs when the stresses on the fixture exceed its structural strength. It can include bolts breaking in the fixture and parts of the fixture breaking or deforming. Fixture breakup can occur from over-speeding of the balancing machine, load imbalance, rapid acceleration or deceleration (such as could be caused by spindle-shaft seizure) of the rotating assembly, and improper assembly of the fixture. Thus, fixture breakup was seen as a possible outcome of spindle-shaft seizure and was developed further in this analysis.

Fig. 3. Close-up of face-plate section of balancing machine.

Fig. 4. Spindle shaft hydraulic bearing assembly.

Fig. 5. Hydraulic oil system

- **Rotating Fixture Strikes Stationary Object**

The rotating fixture can strike a stationary object such as the alignment pole. This could occur from precession of the fixture about its longitudinal axis of rotation or when it is rotating about a single face-plate attachment bolt. A single bolt attaching to fixture and the face plate could result from rapid deceleration; hence, this accident condition is a potential result of shaft seizure. An unattached fixture that is rotating on the face plate probably would begin to precess about its axis of rotation. If the precessional angle becomes large enough, the fixture could strike the alignment pole. Thus, loss of attachment at the face plate is a potential result of spindle-shaft seizure.

- **Fixture Ejection**

The fixture containing an RV can be ejected from the balancing machine during operation. This accident requires a loss of attachment of the fixture to the balancing machine and upsetting moments that cause the fixture to depart from stable upright rotation. These accident sequences are discussed further later in this report because they could result from spindle-shaft seizure. Loss of fixture attachment could result from face-plate bolt failure, single shaft-bolt failure, or spindle-shaft failure—all possible results of spindle-shaft seizure.

- **RV Ejection**

An RV will impact on a stationary object it is ejected from a rotating fixture. This could occur if the fixture precesses rapidly about its axis of rotation or if it rotates about a single bolt on the face plate. This could result from bolt failures or improper assembly.

In addition to spindle-shaft seizure, another possible cause of rapid deceleration of the rotating assembly identified on the fault tree is the sudden seizure of the drive train that transmits power from the motor to the belt. For example, this could result from bevel gear seizure. However, tests with the spare balancing machine at Pantex showed conclusively that the belt driving the face plate will slip under very low torque conditions. Even holding the

face plate by hand will cause the belt to slip at the small wheel attached to the drive train. Therefore, seizure of the drive train cannot transmit sufficient torque to the face plate to cause it to stop spinning in the short time required to shear bolts or the spindle shaft. Thus, no accident-initiating events that could result in seizure of the drive train were examined in this analysis.

In addition to rapid deceleration, other causes of RV impact include improper assembly of the fixture or major load imbalances. These accident causes were not examined further in our analysis.

Two other causes of RV impact that are of interest are over-speed of the assembly and improper installation of bolts. Over-speed can result in shaft seizure, and improper bolt installation can result in RV impact as well exacerbate the effects of spindle-shaft seizure. An over-speed condition will increase the stress on the bolts and shaft during rapid deceleration from shaft seizure and will increase the effects of precession or rotating about a surviving bolt. Improper bolt installation may decrease the ability of the bolts to hold during deceleration and increase the probability of bolt failures leading to RV impact accidents. For these reasons, over-speed and improper bolt installation were analyzed further. Conditions leading to overspeed of the DB machine are addressed in a separate report by Konkel (1997). A fault tree addressing bolt shearing was developed to catalog bolt quality and installation conditions that could contribute to bolt shearing given spindle-shaft seizure. This fault tree is shown in Appendix B.

4.0. FAILURE MODES AND EFFECTS ANALYSIS OF THE SPINDLE, PLATE, AND FIXTURE

As discussed in Sec. 3, the RV impact fault tree demonstrated that spindle-shaft seizure potentially could cause any of the RV impact modes. The next step in the analysis was to examine the mechanisms for spindle-shaft seizure leading to RV impact in greater detail. The first step in this examination was a failure modes and effects analysis (FMEA) of the components that comprise what we call the torsional train of the rotating system. The torsional train is the set of components that transmit rotational energy from the prime mover (motor) to the fixture and RV. Any seizure in the spindle shaft will transmit a decelerating torque through the torsional train to the fixture and RV. Members of the torsional train include the spindle shaft, the face plate, the fixture, and the bolts that hold these components together. Four bolt sets were examined in the FMEA: (1) the **fixture bolts** (the four to eight bolts that hold the halves of the fixture together), (2) the **face-plate bolts** (the bolts that attach the fixture to the face plate through the fixture lower flange), (3) the **flange bolts** (the bolts that attach the face-plate flange to the face plate), and (4) the **shaft bolts** (the bolts that attach the spindle shaft to the face plate). In the FMEA, it was determined that the flange bolts were not a part of the torsional train and that their failure would not result in detachment of the fixture from the spindle shaft, so this bolt set was not considered further. In addition, no components upstream of the face-plate drive belt in the torsional train were considered because, as was mentioned in the previous section, tests showed that seizure of components upstream of this belt would result in belt slippage instead of rapid deceleration of the face plate.

The results of an FMEA on bolts and other parts in the spindle, face plate, and fixture are presented in Table 1. This FMEA explores the effects of shearing different bolt sets and components in the spindle assembly. Only components whose failure could result directly in the accident were examined. Failures that could lead to shaft seizure were identified using a fault tree as discussed in Sec. 5. All of the components examined in the FMEA are shown in Figs. 2 through 4.

Table 1
FMEA of Hydraulic Spindle and Fixture Parts

Component	Failure Mode	Failure Effect
Fixture Bolt Set	All bolts sheared in two by seizure of spindle during balancer operation	Loss of attachment of top half of fixture containing RV from lower fixture. This allows the top half of the fixture to continue spinning without the constraints on precessional motion provided by the bolts.
	All but one bolt sheared in two by seizure of spindle during balancer operation	Changes fixed point attachment of fixture half containing RV. Now the fixture will try to spin around the edge of the lower fixture half with about one-half of the original angular velocity.
Face-Plate Bolt Set	All bolts sheared in two by seizure of spindle during balancer operation	Loss of attachment of fixture containing RV from face plate. This allows the fixture to continue spinning without the constraints on precessional motion provided by the bolts.
	All but one bolt sheared in two by seizure of spindle during balancer operation	Changes fixed point attachment of fixture containing RV. Now the fixture will spin around the edge of the face plate with about one-half of the original angular velocity.
Flange Bolt Set	All bolts sheared in two by seizure of spindle during balancer operation	Loss of attachment of flange to face plate. The flange is used to align the fixture to the face plate during mating and does not affect the fixture attachment
	All but one bolt sheared in two by seizure of spindle during balancer operation	None
Spindle-Shaft Bolt Set	All bolts sheared in two by seizure of spindle during balancer operation	Loss of attachment of spindle to face plate. This allows the face plate to spin on the spindle shaft.
	All but one bolt sheared in two by seizure of spindle during balancer operation	None
Spindle Shaft	Shearing of shaft because of seizing of shaft during balancer operation	Allows the face plate to continue spinning even though the spindle shaft is seized below the fracture.
	Shearing of shaft near top of lower radial bearing during balancer operation.	The end of the shaft could wobble in the radial direction and jam into the bearing housing, causing rapid seizing of the rotating shaft.
Upper Bearing Housing Bolt Set	Shearing during balancer operation	Allows radial misalignment of the spindle shaft. Allows leak of hydraulic fluid from the housing.
Lower Bearing Housing Bolt Set	Shearing during balancer operation	Allows radial misalignment of the spindle shaft. Allows leak of hydraulic fluid from the housing.
Bevel Gears	Jamming	Sudden stoppage of the bevel gears will result in slippage of the belt that transmits torque from the small wheel attached to the drive train to the large wheel attached to the spindle shaft. This was verified by testing during balancer disassembly.
Domsel-Seal Seal Rings Roller Bearing Grease	Breakdown or loss	Loss of shaft lubrication and sealing at upper and lower seals.

5.0. FAULT TREE OF SPINDLE-SHAFT SEIZURE

Using the RV impact fault tree and spindle parts FMEA, we have demonstrated that seizure of the spindle shaft is a potential initiating event for RV impact accident sequences. The next step of the analysis was to develop a qualitative fault tree from the top event "Spindle-Shaft Seizure." The purpose of this fault tree was to help identify potential causes of spindle-shaft seizure at the event, human action, and component levels, not to provide a basis for quantitative estimation of the likelihood of different causes of spindle-shaft seizure. Further development of the fault tree would be required for frequency estimation. The full fault tree is in Appendix C and is separated into five major divisions, which are discussed separately below.

- **Excessive Load Imbalance**

An excessive load imbalance could result in rotational moments on the spindle shaft that would over-stress the radial bearings or bearing housing seals and result in shaft seizure. The vibration detection shutdown system is designed to detect such excessive imbalances and shut down the drive motor.

- **Failure of Axial Bearing**

Failure of the axial bearing system during operation could result in shaft seizure. Both the main axial bearing and the roller bearing would have to fail for the shaft to lose all axial support and seize on contact with the housing. The modes of main bearing failure in the fault-tree model are loss of lubrication, severe over-speeding, or overload of the balancing machine and overheating of the bearing despite continued lubrication.

- **Failure of Radial Bearing**

Failure of either of the radial bearings could result in shaft seizure. These babbitt-lined journal bearings could seize from over-speeding, over-heating, or insufficient lubrication. The babbitt-lined bearings are designed to wipe before seizing, so the shaft would have to continue to rotate after loss of lubrication until the babbitt was wiped away so that metal-to-metal galling and seizure could occur.

- **Failure of Bearing Housing Seals**

Failure of the bearing housing seals could result in shaft seizure. The seals are loaded with grease to contain the hydraulic fluid. Mechanical failure of the seal or loss of lubrication may lead to mechanical galling, and seizure might result.

- **Catastrophic Failure of the Spindle Shaft**

Gross catastrophic torsional failure of the spindle shaft clearly could result in seizing of the shaft. This type of failure could result from pre-existing mechanical flaws in the shaft. However, the shaft is robust and is rather lightly loaded in torsion during operation.

The cut sets of the Spindle-Shaft Seizure fault tree are event sequences that result in shaft seizure. Such event sequences typically consist of an initiating component or system failure followed by protective system or function failures and conditioning events. Table 2 is a list of initiating component failures that could lead to spindle-shaft seizure along with the protective features of the machine designed to prevent or mitigate the consequences of the failure abstracted from the cut sets of the Spindle-Shaft Seizure fault tree.

The initiating events in Table 2 were identified from the cut sets of the spindle-shaft seizure fault tree. A typical cut set from the spindle-shaft seizure fault tree is a Boolean equation of the form

$$\{\text{Cut Set}\} = \{\text{Initiating Event}\} \cap \{\text{Protective Feature Fault}\} \cap \{\text{Enabling Conditions}\}.$$

Table 2
Spindle-Shaft Seizure Initiating Events and Protective Features

Initiating System or Component	Initiating Event Failure Mode	Protective Feature
Load	Imbalance	Excessive vibration shutdown
Speed Controller	Over-speed	Speed controller and speed-limiting features
Hydraulic Oil Pump	Fail to run	Nitrogen bladder oil reservoir
Oil Cooler Heat Exchanger	Loss of cooling capability	Operator action required on high temperature
Oil Temperature Control	Failure high	High-temperature warning light
Chilled Water	Loss	High-temperature warning light
Oil Filter	Plugging	Differential pressure measurement warning light
Oil	Breakdown	Preventive maintenance scheduled to preserve oil quality
Oil Lines	Break	Check valves to limit back flow. Bladder reservoirs. Low-oil-pressure shutdown
Oil Lines	Plugging	Low-oil-pressure shutdown
Oil Relief Valve	Open	Low-oil-pressure shutdown
Radial or Axial Bearing	Primary failure	None
Spindle Shaft	Break	None
Bearing Housing Seal	Seizure	None
Bearing Housing Seal	Leakage	Low-oil-pressure shutdown
Bearing Housing	Leak or rupture	Low-oil-pressure shutdown
Electrical Power	Loss	Nitrogen bladder oil reservoir

The initiating event is a component fault (e.g., hydraulic oil line break) or an external event (e.g., loss of electrical power). The system component that suffers the initiating event is shown in the "Initiating System or Component" column of Table 2. The failure mode of the initiating system or component is shown in the "Initiating Event Failure Mode" column of the same table. If there is a feature in the hydraulic oil system that tends to prevent or mitigate the effects of the accident initiating event, then a protective feature fault is included in the cut set. This protective feature fault represents the failure of the protective feature to prevent or mitigate the accident sequence set in motion by the occurrence of the initiating event. The protective features for each cut set are shown in the "Protective Feature" column of Table 2.

Enabling conditions are system states or conditions that, if present, can enable or exacerbate an accident sequence. For the spindle-shaft seizure accident sequences, we identified an over-speed condition and improper bolt installation as enabling conditions for all of the initiating events in the spindle-shaft seizure tree. The likelihood of bolt or shaft shearing increases with angular velocity of the spindle, and the outcomes of all the accident sequences are exacerbated by increased angular velocity as well. Improper bolt installation, which includes the use of substandard bolts as well as incomplete installation, can increase the probability of bolt shear given a spindle-shaft seizure. These two enabling conditions were explored using separate fault trees as discussed in Appendix B and the report by Konkel (1997).

We could not identify protective features in the current dynamic balancer system for some important initiating events leading to spindle-shaft seizure. These events included primary spindle shaft failure, some hydraulic oil line breaks, primary bearing failure, or bearing housing seal seizure. A primary shaft failure could result in a sudden seizure of the bearing. A primary shaft failure could occur when the machine is operating within design specifications, but a flaw in the shaft results in failure at stresses below its design limits. Such flaws could arise from fabrication faults or from fatigue, corrosion or other aging phenomena. No preventive or mitigating features that could affect spindle-shaft seizure caused by this initiating event were identified.

Some hydraulic oil line breaks may not be mitigated by the low-pressure shutdown and nitrogen bladder injection system. If the line break occurs down stream of the injection point for the nitrogen bladder system, the bearing oil injected by the bladders will not reach the bearings because the injected oil will flow out the break. As a result, the bearing may seize either before shutdown or during the coastdown after the low-pressure shutdown. The bearing may survive for a while on the residual oil film, but the system is not specifically designed to protect against oil line ruptures.

A primary failure of the bearing under normal operating conditions might occur because of a fabrication fault or wear and could result in a shaft seizure. We could not identify any specific protective feature for this type of failure. The bearing housings are labyrinth gland seals that fit around the shaft with tight tolerances and conceivably could seize the shaft. These seals may not be massive enough to seize the shaft without breaking up. No feature to prevent this seizure mode was identified.

Protective features were identified for all other initiating events in the Spindle-Shaft Seizure fault tree. Experience with hydraulic bearings has shown that shaft seizure in a fraction of a revolution is possible (Knapp 1997). Many of the protective features identified for the dynamic balancing machine only act over a time period that is long compared with the time for a revolution (about $1/5^{\text{th}}$ of a second at nominal speeds.) The success of the protective features for loss-of-bearing-lubrication initiating events relies on sensing abnormal conditions that are precursors to loss of oil or oil overheating. In addition, loss of oil flow from loss of the oil pumps is protected against by tripping the balancing machine motor on low oil pressure and then supplying oil from nitrogen pressurized bladders during DBM shaft coast-down. An excessive load imbalance

6.0. CAUSE-CONSEQUENCE DIAGRAMS OF SHAFT-SEIZURE ACCIDENT SEQUENCES

CCA is useful when an accident-initiating event is specified and both the potential causes and potential consequences of these initiating events are sought. This is the situation for the dynamic balancing machine shaft-seizure accidents, where a set of initiating events is specified as spindle-shaft seizure resulting in shaft or bolt shearing. CCD was chosen as the analysis tool for describing and organizing the accident sequences resulting from shaft seizure. It was chosen over the event-tree approach because of the nature of the accident sequences. The accident sequences included many branches dependent on the physical conditions encountered in the balancing machine system under accident conditions. It was also desirable to describe intermediate physical states that continued for some time until transition to another state. CCDs can handle all of these requirements more efficiently than an event tree, and experience has indicated that CCDs often are easier for engineers to understand than event trees.

Four CCDs were generated from the initiating event "Spindle-Shaft Seizure." Each models different failure modes that result from shaft seizure. The failure modes are fixture-bolt shear, face-plate bolt shear, spindle-shaft bolt shear, and spindle-shaft shear. The implicit assumption made in this analysis is when any set of bolts or the shaft fails, the other components survive. This may be a simplification because it is conceivable that some members of several bolt sets could fail. This complication was not examined in detail but did not appear to lead to any new accident sequence classes.

The CCDs for each failure mode are discussed in the following sections. Each path through the CCD beginning with the initiating event and ending with a consequence is a possible accident sequence. The consequences in our analysis only cover the accident progression to the point that the RV either decelerates and comes to rest on the balancing machine or leaves the balancing machine with some translational and angular velocities. We assumed that all accident sequences that eventually end with the RV at rest and still on the balancing machine are desirable outcomes. All of the accident sequences that lead to the RV leaving the balancing machine are undesirable and need to be analyzed further to determine the final state of the RV when it strikes some object in the bay or finally comes to rest in some other way. This analysis attempts to provide estimates of the maximum translational and angular velocities that the RV may have when it leaves the balancing machine under various accident conditions using simple physical models. The models are not for detailed prediction, which would require advanced numerical simulation for many of the accident sequences. They are intended only to guide the analyst in constructing sensible and realistic

accident sequences and in determining which values of the accident parameters might lead to which types of accident sequences.

In all of the following accident sequences we assume that the spindle shaft, face plate and fixture are all spinning at some steady angular velocity of ω . The motion of the spindle shaft then is arrested during some fraction of a revolution by seizure of the spindle shaft. As a result of the stopping impulse, one of the bolt sets or the shaft suffers shear failure. We assume that if two or more of any bolt set survive, then the surviving bolts transmit the stopping torque to the next component down the line and bring it to rest. We recognize that the RV may continue to rotate about its longitudinal axis even if the fixture comes to rest because the RV is not held rigidly to the fixture but is linked only by friction, and this is included in the calculations. When precessional motion is described in the text, the angular velocity of the primary axis of rotation about the vertical is denoted by α and is referred to as the precessional angular velocity. The angle between the primary axis of rotation and the axis about which it precesses is called the precessional angle and is denoted by the symbol θ . We recognize that steady precession is an idealization of the probable motion and that nutation and increasing precessional angle are likely complications. However, all of our idealized calculations assume steady precession and frictionless motion for simplicity.

The CCD for the failure of face-plate bolts is discussed in some detail to help the reader become familiar with the CCD concept. Subsequent CCDs will be covered less extensively.

6.1. Face-Plate Bolt Shear

Failure of a sufficient number of face plate bolts would lead to formation of a rotating assembly consisting of the fixture and RV. The accident sequences for spindle-shaft seizure leading to face-plate bolt shear were developed by application of the elementary physics of both constrained and free rotating bodies. Based on this reasoning, we developed accident sequences that captured the essence of the physical models. These accident sequences are shown graphically in a CCD shown in Fig. 6. All the accident sequences may be constructed from the CCD by tracing all the paths from the initiating event to each consequence node. In this CCD, "Spindle-Shaft Seizure" is shown as an initiating event. As a result of this initiating event, either two or more or one or no face plate bolts may survive. The accident progression will differ radically depending on the number of surviving bolts because of the widely different types of motion imparted to the fixture and RV. Thus, an important set of branching operators in the CCD is whether all bolts shear nearly simultaneously or one bolt survives significantly longer than the others.

Following the director arrow from the initiating event, we see that four different accident classes are addressed. Three of these are shown as continuation circles and are covered on other CCDs. The fourth director leads to the first branch operator in the CCD with text "Two or more face-plate bolts survive." If two or more bolts survive, we assume that the fixture is arrested in its rotation successfully. This outcome is shown as the terminus of the director from the Yes branch of the branch operator. The No branch leads to a second branching operator titled "One face-plate bolt survives." The Yes branch of this operator leads to the event descriptor "Fixture begins to rotate around surviving bolt." The No branch leads to the condition where no bolts hold the fixture to the face plate and the fixture is in free rotation about its vertical axis. These conditions are very different and are discussed separately.

The accident sequences shown on the CCD are found by tracing all director paths from the initiating event until a consequence descriptor is reached. These paths are listed on different rows in Table 3. In this table, only the branching operators are shown on each path. The abbreviations shown on the CCD for each branching operator are listed as column headings along the top of the table. If a branching operator is in the path, there will be a Y or an N in the table entry, depending on whether the path follows director emanating from the Yes or No branch of the operator. The next-to-last column on the right shows the consequence descriptor for each accident sequence. In the last column, the effect of the accident consequence on the RV is shown. If the accident consequence does not lead to RV impact, then an OK is entered.

Fig. 6. Face-plate bolt shear cause-consequence diagram.

Fig. 6. Face-plate bolt shear cause-consequence diagram (continued).

Table 3
Summary of Face-Plate Bolt Shear Accident Sequences

Event Sequence	Branch Operators									Consequence	
	TFP	OFF	RBS	UFP	SBB	DRV	AVS	SAP	SBS	Outcome	Effect
1	Y									FA	OK
2	N	Y	Y							FFO	
3	N	Y	N		Y	Y				RVE	
4	N	Y	N		Y	N		N	Y	FFO	
5	N	Y	N		N		Y			RVE	
6	N	Y	N		N		N			SFR	OK
7	N	Y	N		Y	N		N	N	SFR	OK
8	N	Y	N		Y	N		Y		IAP	
9	N	N		Y						SD	OK
10	N	N		N						SFF	

Each of the accident sequences developed for the spindle-shaft seizure leading to face-plate bolt shear is discussed in detail below. The terminology used in these discussions is described here. The same terminology also will be used in the discussion for the other CCDs that are described in the remainder of this study. The accident sequences for face-plate bolt shear are each tagged with a unique identifier of the form **FPBS-x**. In this identifier, **x** is the accident sequence number from Table 3. The Boolean expression for the accident sequence is given in brackets. These Boolean expressions are of the form $\{A \cap B \cap C\}$. A term such as **A**, which is neither underlined or italic, represents the **Yes** branch of branch operator **A**. The term **B**, which is underlined, represents the **No** branch of branch operator **B**. A term such as ***C*** that is in italics is a consequence. Each of the terms in the Boolean equation is addressed in the discussion of the first accident sequence in which it is found.

6.1.1. Accident Sequence FPBS-1: $\{TFP \cap FA\}$. In this accident sequence, spindle-shaft seizure occurs and all of the chain of components that transmits the torsional energy from the shaft through the fixture survives. In addition, at least two face-plate bolts survive. This event is described symbolically in the Boolean equation for the accident sequence by **TFP** which is a **Yes** for the TFP branch operator in the CCD. If two face-plate bolts survive, then we assume that the fixture is brought to rest at the same time as the seized shaft. This is indicated by the consequence **FA** in the Boolean equation for the accident sequence. In this accident sequence, the RV is safely brought to rest in a fixture that is still attached to the DBM, so the outcome has an OK in the far right column of Table 3.

6.1.2. Accident Sequence FPBS-2: $\{\underline{TFP} \cap OFF \cap RBS \cap FFO\}$. In this accident sequence, two face-plate bolts do not survive (**TFP**), but one face-plate bolt does survive (**OFF**). This single surviving face-plate bolt becomes the axis of rotation for the fixture, but after the fixture starts to rotate around the bolt, it shears off (**RBS**), resulting in the fixture leaving the DBM (**FFO**).

OFF: If all of the face plate bolts except one shear, then the surviving bolt would exert a stopping force against the fixture to prevent its rotation about its vertical axis. This would result in a translational force on the fixture center of mass and would start the fixture rotating about the surviving bolt at rotational velocity α . This situation is shown in Fig. 7 for a fixture with the same diameter as the face plate. In this rotational mode, the center of mass of the fixture/RV system is rotating around the surviving bolt. Based on the simple consideration in Appendix F, the angular velocity α could be a maximum of about $\frac{1}{2}$ of the original ω of the spinning assembly.

RBS: This accident progression places tremendous demands on the surviving bolt. It must absorb a significant fraction of the energy of the fixture/RV system and then release it into the system again to change the rotational axis. The only way this could happen is if most of the energy in the system was absorbed in shearing off the other face-plate bolts so that very little is left to shear the final bolt or if the surviving bolt was much stronger than the sheared bolts.

Fig. 7. Geometric model for survival of one face-plate bolt.

FFO: The RV motion for the consequence FFO will consist of both translational and rotational components. If the surviving bolt fails after the fixture/RV system starts rotating about it, then the center of mass of the fixture/RV system will continue along a trajectory tangential to its rotational path. The velocity will be (αa) , where a is the radius of the fixture. This is the tangential velocity of the center of mass during rotation about the surviving bolt. The fixture-RV system also will have rotational velocity about its longitudinal axis of value α as it flies through the air because of the rotational motion of the fixture about the bolt. This can be seen readily from both conservation of rotational energy and tracing of the motion of the fixture edges during rotation about the surviving bolt. The RV also may have an angular velocity near ω about its longitudinal axis because it is not rigidly attached to the fixture and will not necessarily be stopped in its original rotation by the surviving bolt. The fixture could either land on the floor and tumble across the floor or fly through the air until it strikes a wall or other objects in the bay.

6.1.3. Accident Sequence FPBS-3: {TFP $\cap$ OFP $\cap$ RBS $\cap$ SBB $\cap$ DRV $\cap$ RVE}. This accident sequence is similar to **FPBS-2** in that one face-plate bolt survives (**OFP**). This single surviving face-plate bolt becomes the axis of rotation for the fixture, and continues to survive even after the fixture starts to rotate around the bolt (**RBS**). However, the surviving bolt bends (**SBB**). During this rotational motion about the surviving bolt, the RV is ejected from the fixture (**DRV**), resulting in the consequences of such an ejection (**RVE**).

RBS: If the bolt survives long enough, the fixture-RV system will rotate around the surviving bolt. The radius of the circle described by the center of mass will be near the fixture radius as can be seen in Fig. 7. This will result in considerable centrifugal force on the R.

SBB: There is a high likelihood that the surviving bolt will bend when the RV rotates to where its center of mass is off the face plate. The decking is lower than the face plate, so the surviving bolt will experience a bending moment when the RV center of mass is over the decking. This may break the bolt or cause it to bend. The angle θ in Fig. 7 to which the fixture can bend is limited by the decking to fairly small values.

DRV: We can see from Appendix E that if the rotational velocity is high enough, the RV could be ejected from the fixture if the restraining mechanism that holds the RV in the fixture at the top is not strong enough to resist the centrifugal acceleration generated by the motion. This effect is exacerbated by bending of the face-plate bolt so that the fixture axis is inclined to the vertical (the angle θ in Fig. 7). In addition, because the RV is not rigidly attached to the fixture, the RV could still be spinning around its longitudinal axis at a high rate inside the fixture and will continue this motion after it is ejected.

RVE: In this accident sequence, the RV would have some translational motion imparted by the rotation around the surviving bolt. The ejected RV also would have rotational velocity about its own longitudinal axis. It would be likely to tip as it is ejected from the fixture and tumble to the bay floor. The RV then could roll or tumble across the bay floor until it strikes a stationary object or wall in the bay.

6.1.4. Accident Sequence FPBS-4: {TFP $\cap$ OFF $\cap$ RBS $\cap$ SBB $\cap$ DRV $\cap$ SAP $\cap$ SBS $\cap$ FFO}. This accident sequence is similar to FPBS-2 in that one face-plate bolt survives (OFF). This single surviving face-plate bolt becomes the axis of rotation for the fixture and continues to survive even after the fixture starts to rotate around the bolt (RBS). However, the surviving bolt bends (SBB). During this rotational motion about the surviving bolt, the RV is not ejected from the fixture (DRV). The rotating fixture does not strike the alignment pole that is placed near the edge of the DBM (SAP). The bolt bends in this sequence as the fixture center of mass moves off the face plate. This will require that the fixture ride back up to its initial position as its edge encounters the edge of the face plate. In this accident sequence, this encounter leads to shearing of the remaining bolt (SBS) and fixture fly off (FFO) as in accident sequence FPBS-2.

6.1.5. Accident Sequence FPBS-5: {TFP $\cap$ OFF $\cap$ RBS $\cap$ SBB $\cap$ AVS $\cap$ RVE}. This accident sequence is similar to FPBS-3 in that one face-plate bolt survives (OFF). This single surviving face-plate bolt becomes the axis of rotation for the fixture and continues to survive even after the fixture starts to rotate around the bolt (RBS). The surviving bolt does not bend (SBB). During this rotational motion about the surviving bolt, the RV is ejected from the upright (AVS), resulting in the consequences of such an ejection (RVE) as in accident sequence FPBS-3.

AVS: In Appendix E, it is shown that the RV may be ejected from an upright fixture rotating around the surviving bolt because of the conical shape of the RV and the matching supports in the fixture. Thus, even if the surviving bolt does not bend, RV ejection is a possibility during rotation around a single bolt.

6.1.6. Accident Sequence FPBS-6: {TFP $\cap$ OFF $\cap$ RBS $\cap$ SBB $\cap$ AVS $\cap$ SFR}. This accident sequence is almost identical to FPBS-5 except that during rotational motion about the surviving bolt, the RV constraining ring at the top of the fixture is strong enough to prevent ejection from the upright (AVS). In this case the fixture and RV continue to rotate around the surviving bolt until the motion is stopped by friction (SFR). In this accident sequence, the RV is safely brought to rest in a fixture that is still attached to the DBM, so the outcome has an OK in the far right column of Table 3.

6.1.7. Accident Sequence FPBS-7: {TFP $\cap$ OFF $\cap$ RBS $\cap$ SBB $\cap$ DRV $\cap$ SAP $\cap$ SBS $\cap$ SFR}. This accident sequence is identical to FPBS-4 except that when the fixture rides back up to its initial position as its edge encounters the edge of the face plate the remaining bolt survives (SBS). This motion continues until the fixture and RV come to rest still attached to the DBM by one bolt (SFR) as in accident sequence FPBS-6. In this accident sequence, the RV is safely brought to rest in a fixture that is still attached to the DBM, so the outcome has an OK in the far right column of Table 3.

6.1.8. Accident Sequence FPBS-8: {TFP $\cap$ OFF $\cap$ RBS $\cap$ SBB $\cap$ DRV $\cap$ SAP $\cap$ SAP}. This accident sequence is identical to FPBS-4 up to the point that the rotating fixture strikes the alignment pole (SAP). This results in an impact of the fixture containing the RV with the pole with consequence (IAP)

SAP: In Appendix G, conditions under which the fixture will strike the alignment pole as it rotates around the surviving bolt are examined. When the diameter of the fixture is close to that of the face plate, the probability of the fixture striking the pole as it rotates around a single bolt is about 0.5. For a fixture with a smaller diameter, the

probability decreases monotonically toward zero. The fixture will strike the pole with a maximum angular velocity of about $1/2\omega$ (see appendix F.)

IAP: The alignment pole has fairly lightweight metal walls and probably will be sheared off by the impact of the fixture. The surviving fixture bolt probably will shear off at the impact as well. Thus, the fixture and RV may have some translational velocity after the pole impact. The fixture and RV will likely tumble to the bay floor and roll or tumble across the floor.

6.1.9. Accident Sequence FPBS-9: {TFP $\cap$ OFF $\cap$ UFP $\cap$ SD}. In this accident sequence, all of the face-plate bolts shear off more or less simultaneously (**TFP $\cap$ OFF**) and the fixture rotates like a top on the face plate without significant unbalanced translational forces or upsetting torque (**UFP**). The fixture may precess but remains upright and on the face plate. The fixture and RV gradually decelerate and eventually come to rest still standing upright on the face plate (**SD**).

UFP: The fixture-RV system is balanced very carefully during mass properties testing so that the center of mass of the system is very closely aligned along the axis of rotation. If all the face-plate bolts shear simultaneously and instantaneously, the system composed of the fixture and RV ideally will continue to spin like a cylindrical gyroscope around the longitudinal (initially vertical) axis. This rotational velocity could be close to the original angular velocity ω if the energy required to shear the bolts is only a small fraction of the available torsional energy in the system. The situation is different if a large fraction of the original energy is required to overcome the static frictional force imposed by the bolt torque between the face plate and fixture lower flange and then shear the bolts. In this case, the rotational energy of the unattached fixture-RV system will be reduced considerably below the original rotational energy of the same system. This idealized gyroscopic motion probably would not last very long because of non-uniform contact between the face plate upper surface and the fixture lower flange surface.

During precessional motion of the spinning fixture, the center of mass of the RV rotates about the vertical axis, so RV ejection is theoretically possible. In Appendix E, we show that RV ejection by precession is very unlikely unless the dynamic balancer severely over-speeds or during the last stages of the fixture tipping over. This is because the radius of rotation and the precessional angular velocity are both quite small.

6.1.10. Accident Sequence FPBS-10: {TFP $\cap$ OFF $\cap$ UFP $\cap$ SFF}. This accident sequence is identical to **FPBS-9** except that the fixture/face-plate contact is nonuniform (**UFP**). The fixture/RV system 'walks off' the face plate onto the deck where it may continue to walk to the edge and tumble from the DBM or it may depress the decking and tip over while still on the DBM decking. The consequence is term (**SFF**) in either case.

UFP: The face-plate shear conditions for the situation where the fixture and face plate have the same diameter are shown in Fig. 8. This illustration shows the fixture as it "walks" off the face plate and onto the surrounding decking. This walking motion is generated by nonuniform contact between the fixture flange and face plate, which will create translational motion and torque about the system center of mass and axis of rotation. At high rotational speeds, this motion could occur very rapidly.

The bottom of the fixture will be moving relative to the face plate, and friction will occur. Nonuniformity in the contact between the fixture and face plate will result in unbalanced forces around the fixture/face-plate contact area. These forces will cause translational motion of the center of mass of the fixture assembly. The spinning upright fixture probably will move in a more or less random "walk" toward an edge of the face plate with some precessional motion at angular velocity α about its axis of revolution as well. When the center of mass of the fixture reaches the edge of the face plate, the fixture can start to tip from the vertical because of the torque created by the gravitational force on the center of mass. This torque can create more precessional motion. It would not appear that the unit can tip far enough before contacting the decking that surrounds the face plate to tip over onto its side on the decking and roll off the machine onto the floor. Instead, a reasonable scenario is for the fixture to "walk" onto the decking and continue to walk across the decking until it finally tips over the edge and falls to the floor.

Fig. 8. Geometric model for shearing of all face-plate bolts.

SFF: The fixture assembly could still be spinning quite rapidly about its longitudinal axis when it tips over or falls from the table and so could roll or tumble rapidly across the floor, potentially striking the hydraulic control cabinet, tables, or wall. The rolling velocity will depend on the slippage of the rotating fixture and the residual angular velocity about the longitudinal axis of the fixture.

6.1.11. Summary of Face-Plate Bolt Shear Accident Sequences. Shearing of the face-plate bolts because of spindle-shaft seizure could result in three distinct types of motion with differing accident consequences. If all other components in the torsional train from the spindle shaft to the fixture survive the spindle-shaft seizure and two or more face-plate bolts survive, then the fixture will be arrested by the spindle-shaft seizure without impact of the RV on any stationary objects in the bay. If only one face-plate bolt survives, the fixture-RV system can begin to rotate about the surviving bolt. In this situation, fly-off of the fixture-RV system is possible. Impact of the fixture on the alignment pole is also a possible accident outcome. Finally, ejection of the RV from the rotating fixture could also occur. If no face-plate bolts survive the initial deceleration transient, then the fixture could spin like a top until coming to rest on the face plate, or could 'walk-off' the DBM and tumble to the bay floor still spinning at near its original angular velocity.

6.2. Fixture-Bolt Shear or Fixture Failures

Failure of the bolts used to assemble to top and bottom segments of the RV fixture would result in a detached assembly consisting of the RV and upper segment of the fixture. This detached segment would form a rotating assembly. The accident sequences for spindle-shaft seizure leading to fixture bolt shear were developed by application of the elementary physics of both constrained and free rotating bodies. Based on this reasoning, we generated accident sequences that captured the essence of the physical models. These accident sequences are shown graphically in a CCD shown in Fig. 9. All the accident sequences may be constructed from the CCD by tracing all the paths from the initiating event to each consequence node. In this CCD, "Spindle Shaft Seizure" is shown as an initiating event. As a result of this initiating event, one or more or no fixture bolts may survive. The accident sequences from this CCD are summarized in Table 4.

Table 4
Summary of Fixture-Bolt Shear Accident Sequences

Event Sequence	Branch Operators					Consequence	
Event Sequence	TFP	UFP	COM	DRV	SAP	Consequence	Effect
1	Y					FA	OK
2	N	Y				SD	OK
3	N	N	Y			SFF	
4	N	N	N	Y		RVE	
5	N	N	N	N	Y	IAP	
6	N	N	N	N	N	SD	OK

Each of the accident sequences developed for the spindle-shaft seizure leading to fixture bolt shear is discussed in detail below. The terminology used in these discussion is described here. The same terminology also will be used in the discussion for the other CCDs that are described in the remainder of this study. The accident sequences for fixture-bolt shear are each tagged with a unique identifier of the form **FBS-x**. In this identifier, **x** is the accident sequence number from Table 4. The Boolean expression for the accident sequence is given in brackets. These Boolean expressions are of the form $\{A \cap \underline{B} \cap C\}$. A term such as **A**, which is neither underlined or italic, represents the **Yes** branch of branch operator **A**. The term $\underline{B}$, which is underlined, represents the **No** branch of branch operator **B**. A term such as *C* that is in italics is a consequence. Each of the terms in the Boolean equation is addressed in the discussion of the first accident sequence in which it is found.

6.2.1. Accident Sequence FBS-1: $\{TFP \cap FA\}$. In this accident sequence, spindle-shaft seizure occurs and all of the chain of components that transmits the torsional energy from the shaft through the fixture survives. In addition, at least one fixture bolt survives. This event is described symbolically in the Boolean equation for the accident sequence by **TFP**, which is a **Yes** for the TFP branch operator in the CCD. If one or more face-plate bolts survive, then we assume that the fixture is brought to rest at the same time as the seized shaft. This is indicated by the consequence **FA** in the Boolean equation for the accident sequence. In this accident sequence, the RV is brought to rest safely in a fixture that is still attached to the DBM, so the outcome has an OK in the far right column of Table 4.

TFP: If one of the bolts survives, the top half of the fixture with the RV could begin to rotate about this bolt at angular velocity α , but the RV nose extends a considerable distance into the lower fixture segment and would tend to prevent tipping, limit the precessional angle, and resist rotation about the surviving bolt. Therefore, the single-bolt case is treated the same as if two or more bolts survived in this accident.

6.2.2. Accident Sequence FBS-2: $\{\underline{TFP} \cap \underline{UFP} \cap SD\}$. In this accident sequence, spindle-shaft seizure occurs. As a result, all of the chain of components that transmits the torsional energy from the shaft through the fixture survives except the fixture bolts, which are all sheared. This event is described symbolically in the Boolean equation for the accident sequence by $\underline{TFP}$ which is a **No** for the TFP branch operator in the CCD. If the contact between the upper and lower fixture halves is sufficiently uniform (**UFP**), then the upper fixture half and RV will decelerate in place with out tipping over, leading to a final configuration with the RV still in the upper fixture half which is still atop the lower fixture half (**SD**).

$\underline{TFP}$: If the fixture bolts all fail during deceleration, then the top half of the fixture holding the RV would be detached from the bottom half and could continue spinning at angular velocity ω . The lower flange of the still spinning upper fixture could contact the upper flange of the lower fixture, which is still attached to the now stationary face plate. The situation with all fixture bolts sheared is shown in Fig. 10, which serves as a reference for the remainder of the discussion of the fixture-bolt accident sequences. In the illustration we see a detached upper fixture segment containing the RV and a lower stationary fixture segment still attached to the face plate by the face plate bolts. We also see the extension of the RV nose into the lower fixture segment. A similar set of conditions

Fig. 9. Fixture-bolt shear cause-consequence diagram.

Fig. 9. Fixture-bolt shear cause-consequence diagram (continued).

could occur if some of the fixture structural components failed instead of the bolt sets. For example, stretching of the bolt holes because of the stresses of deceleration also could result in the upper segment of the fixture becoming unattached. Upsetting moments caused by nonuniform contact between the lower flange of the upper fixture and the upper flange of the stationary lower fixture will cause the upper fixture with the RV to precess and wobble about the original axis of rotation before shaft seizure and fixture failure with some angular velocity α and at an inclination angle of θ .

UFP: If the contact between the rotating upper fixture segment and the stationary lower fixture is sufficiently uniform, then the fixture upper half will continue to rotate more or less in its original position while slowing down because of friction. Any nonuniformity in the contact will tend to produce precession and nutation (wobble) of the spinning upper fixture half. During precessional motion of the spinning upper fixture half, the center of mass of the RV rotates about the vertical axis with precessional angular velocity α , so RV ejection is theoretically possible. In Appendix E, we show that RV ejection by precession is very unlikely unless the dynamic balancer severely overspeeds or during the last stages of the fixture upper half tipping over. This is because the radius of rotation and the precessional angular velocity are both quite small. The extension of the RV into the lower fixture will tend to stabilize the upper fixture and provide resistance to tipping over in addition to the gyroscopic action of the spinning upper fixture and RV.

6.2.3. Accident Sequence FBS-3: {TFP $\cap$ UFP $\cap$ COM $\cap$ SFF}. In this accident sequence, spindle-shaft seizure occurs. As a result, all of the chain of components that transmits the torsional energy from the shaft through the fixture survives except the fixture bolts, which are all sheared (**TFP**). The contact between the rotating upper fixture, which contains the RV, and the stationary lower fixture is highly nonuniform (**UFP**), resulting in significant precession and wobble of the upper fixture. The movement of the upper fixture becomes so significant that it tips over and falls off the lower fixture (**COM**). The still spinning upper fixture and RV fall to the balancing machine decking and onto the floor and then roll or tumble across the bay floor (**SFF**).

Fig. 10. Geometric model for fixture-bolt shear.

UFP: Upsetting moments caused by nonuniform contact between the lower flange of the upper fixture and the upper flange of the stationary lower fixture will cause the top half with the RV to precess and wobble about the original axis of rotation with an angular velocity α that could be up to 1/2 the original angular velocity ω of the balancing machine.

COM: If the center of mass of the fixture-RV system is high enough that the gravitational force can pass outside the edge of the lower fixture (point q in the figure) during the precessional motion, then the upper fixture could eventually tip over and fall to the balancing machine decking or floor, especially as the rotational motion of the fixture upper slows because of friction, reducing the gyroscopic action of the spinning upper fixture and RV that tends to resist upsetting motions.

SFF: The upper fixture/RV assembly still could be spinning quite rapidly about its longitudinal axis when it tips over or falls from the top of the lower fixture and so could roll or tumble rapidly across the dynamic balancer decking. It then would tumble to the bay floor and tumble or roll across until striking the hydraulic control cabinet, tables, or wall. The rolling velocity will depend on the slippage of the rotating fixture and the residual angular velocity about the longitudinal axis of the fixture and RV. The RV could be separated from the upper fixture during this motion.

6.2.4. Accident Sequence FBS-4: {TFP $\cap$ UFP $\cap$ COM $\cap$ DRV $\cap$ RVE}. This accident sequence follows the progression of FBS-3 except that the upper fixture/-RV system does not tip over (**COM**). Instead, the RV is ejected during the wobble and precession of the upper fixture (**DRV**). This results in an RV ejection outcome (**RVE**)

DRV: As was mentioned previously, RV ejection is less likely during precessional motion because of the smaller angular velocity and radius of rotation of the RV center of mass. However, in the case of the upper fixture, the RV nose extension will tend to stabilize the motion even for large inclination angles (θ in Fig. 9). This could lead to RV ejection instead of or before fixture tip over (**COM**).

6.2.5. Accident Sequence FBS-5: {TFP $\cap$ UFP $\cap$ COM $\cap$ DRV $\cap$ SAP $\cap$ IAP}. This accident sequence follows the progression of FBS-5 except that the RV is not ejected from the upper fixture (**DRV**). Instead, the fixture strikes the alignment pole during its wobble and precession atop the lower fixture (**SAP**). This results in an alignment pole impact outcome (**IAP**).

SAP: If the fixture diameter is nearly the same as the face-plate diameter, then the alignment pole will be almost one fixture radius from the outer edge of the fixture. During the precession of the upper fixture, the angle θ would have to become very large for the fixture to strike the alignment pole. The center of the upper fixture can move some distance laterally from the center line of the stationary lower fixture and face plate, which could reduce the inclination angle at which the upper fixture segment would strike the alignment pole. Striking this pole could result in shearing the alignment pole and knocking the upper fixture and RV off the top of the lower fixture, with an outcome similar to **SFF** discussed in **FBS-3**.

6.2.6. Accident Sequence FBS-6: {TFP $\cap$ UFP $\cap$ COM $\cap$ DRV $\cap$ SAP $\cap$ SD}. In this accident sequence, the upper fixture/RV system avoids all the undesirable outcomes and wobbles and precesses around atop the lower fixture until coming to rest in that position. This is an identical outcome to **FBS-2**.

6.2.7. Summary of Fixture-Bolt Shear or Fixture Failure Accident Sequences. Shearing of the fixture bolts because of spindle-shaft seizure could result in two distinct types of motion with differing accident consequences. If all other components in the torsional train from the spindle shaft to the fixture survive the spindle-shaft seizure and one or more face-plate bolts survive, then the fixture will be arrested by the spindle-shaft seizure without impact of the RV on any stationary objects in the bay. If no fixture bolts survive the initial deceleration transient, then a rotating assembly consisting of the upper fixture and RV could spin like a top until coming to rest on the upper flange of the lower fixture segment. Alternately, the RV could be ejected from the rotating assembly during precession and nutation of the rotating assembly while spinning atop the lower fixture segment. The entire rotating assembly could also 'walk-off' the lower fixture segment and tumble to the DBM decking or bay floor still spinning at near its original angular velocity.

6.3. Shaft-Bolt Shear

A set of bolts attaches the spindle shaft to the face plate. If these bolts shear during deceleration of the rotating assembly, then the face plate, fixture and RV would constitute a rotating assembly that would continue to spin. The accident sequences for spindle shaft seizure leading to shaft bolt shear were developed by application of the elementary physics of both constrained and free rotating bodies. Based on this reasoning, we generated accident sequences that captured the essence of the physical models. These accident sequences are shown graphically in a CCD shown in Fig. 11. All the accident sequences may be constructed from the CCD by tracing all the paths from the initiating event to each consequence node. In this CCD, "Spindle-Shaft Seizure" is shown as an initiating event. As a result of this initiating event, one or more or no shaft bolts may survive. The accident sequences from this CCD are summarized in Table 5, which is identical in format to Table 3 (the summary of face-plate bolt shear accidents).

Each of the accident sequences developed for the spindle-shaft seizure leading to shaft-bolt shear is discussed in detail below. The terminology used in these discussion is described here. This same terminology also will be used in the discussion for the other CCDs that are described in the remainder of this study. The accident sequences for shaft-bolt shear are each tagged with a unique identifier of the form **SBF-x**. In this identifier, x is the accident sequence number from Table 5. The Boolean expression for the accident sequence is given in brackets. These Boolean expressions are of the form $\{A \cap \underline{B} \cap C\}$. A term such as **A**, which is neither underlined or italic, represents the **Yes** branch of branch operator **A**. The term **B**, which is underlined, represents the **No** branch of branch operator **B**. A term such as ***C*** that is in italics is a consequence. Each of the terms in the Boolean equation is addressed in the discussion of the first accident sequence in which it is found. In the discussions that follow, reference to Fig. 12 will help the reader follow the discussion of the geometric parameters and physical orientation of the rotating assembly.

Table 5
Summary of Shaft Bolt Shear Accident Sequences

Event Sequence	Branch Operators					Consequence	
Event Sequence	SBF	UTP	CPA	PVE	MSD	Outcome	Effect
SBF-1	N					FA	OK
SBF-2	Y	Y	Y		Y	SD	OK
SBF-3	Y	Y	Y		N	CS	
SBF-4	Y	Y	N	Y		RVE	
SBF-5	Y	N			Y	SD	OK
SBF-6	Y	N			N	CS	
SBF-7	Y	Y	N	N		SFF

Fig. 11. Shaft-bolt shear cause-consequence diagram.

Fig. 12. Geometric model of shaft-bolt shear.

6.3.1. Accident Sequence SBF-1: {SBF $\cap$ FA}. In this accident sequence, at least one shaft-bolt survives the spindle-shaft seizure transient (**SBF**). The face plate is press-fitted onto the top of the shaft, so we assume that there is no significant relative motion between the shaft and face plate if the bolt survives. Thus, the face plate is stopped at the same time as the spindle shaft (**FA**).

6.3.2. Accident Sequence SBF-2: {SBF $\cap$ UTP $\cap$ CPA $\cap$ MSD $\cap$ SD}. In this accident sequence, all of the shaft bolts shear as a result of spindle-shaft seizure (**SBF**). The face plate and fixture continue to rotate, undergoing precession and wobbling because of nonuniform contact of the face-plate extension with the bearing plate and deck (**UTP**). The decking and bearing constrain the face-plate/fixture angle of (**CPA**). The drive motor shuts down on an excessive vibration signal (**MSD**). The rotating face-plate/fixture assembly decelerates and stops still more or less upright atop the bearing plate (**SD**).

SBF: The shaft bolts have been identified as the weak link in the torsional train from the spindle shaft to the fixture and the most likely to break.⁸ Calculations indicate that spindle-shaft seizure that results in arresting the rotation of the shaft in slightly less than seven revolutions could shear all the shaft bolts. Experience has shown that even hydraulic bearings can seize and stop in less than one revolution. Thus, a spindle-shaft seizure could be quite likely to shear all this bolt set given the occurrence of spindle-shaft seizure.

UTP: If the shaft bolts are failed, then the face plate is held onto the shaft only by the friction of the press fit used during assembly of the unit. The press-fitting friction is assumed to be overcome so that the face plate continues to spin. The drive-belt tension will provide some torque on the face plate tending to tip it towards the drive pulley. The rotating assembly could tip enough for the lower edge of the face plate extension (see Fig. 3) to contact the bearing plate. Upsetting moments that disturb the upright spinning of the face plate and fixture system in the above-described scenario cause the axis of rotation to tilt at the angle θ from its original orientation as shown in Fig. 12. The fixture/face-plate system then would undergo gyroscopic precession at some angular velocity α around this

original vertical axis as it continued to spin around its longitudinal axis at angular velocity ω . Unlike the familiar gyroscopes, which are designed for stable spin, this system immediately would begin to suffer perturbations and enter a very complicated motion that probably would include significant nutation in which the axis of rotation would wobble.

CPA: The inclination angle θ of the rotating assembly would be constrained by the bottom of the face-plate extension striking the solid top of the bearing plate and the top of the face-plate extension striking the underside of the decking as shown in Fig. 12. The bearing plate is very strong and would provide a strong constraint to the tipping of the rotating assembly. One corner of the bearing plate is a cut so that the extension would only partly contact it in that position. This could allow more tip in this direction than in other directions. The decking would also constrain the angle of tipping. The decking is not as strong as the bearing plate but would provide some constraint to tipping.

MSD: The face plate is driven directly by the drive belt, so the belt could continue to supply energy to the face plate after the shaft bolts sheared and the face plate was unattached. After loss of the shaft bolts, the face plate would not be rigidly attached to the shaft, which gave it lateral stability against the belt tension. Thus, the belt would cause the assembly to wobble. As the assembly wobbled, the belt may drive the face plate only intermittently, even if the motor continues to run after shaft-bolt shearing. The vibration detection system would be expected to sense the excessive vibration caused by the assembly precession and wobble and shut off the motor within three revolution. The belt drive would then rapidly decay away and cease.

6.3.3. Accident Sequence SBF-3: {SBF $\cap$ UTP $\cap$ CPA $\cap$ MSD $\cap$ CS}. This accident sequence is identical to SBF-2 except that the drive motor does not shut off because of an excessive vibration signal (**MSD**).

CS: The CS outcome represents continued driving of an unattached fixture by the drive belt, which is attached to the face plate. This is an unstable condition, but not an accident condition until something happens to lead the accident progression to one of the undesirable paths on the CCDs.

6.3.4. Accident Sequence SBF-4: {SBF $\cap$ UTP $\cap$ CPA $\cap$ PVE $\cap$ RVE}. In this accident sequence, the shaft bolts shear after a spindle-shaft seizure (**SBF**), and the unattached face-plate-fixture assembly begins precessional motion and wobble (**UTP**). This motion is not constrained by the bearing plate and decking sufficiently (**CPA**) to prevent ejection of the RV(**PVE**) with subsequent consequences as outlined above (**RVE**).

PVE: RV ejection would require a sufficient inclination angle θ and sufficient precessional angular velocity α . These conditions are not likely to be achieved during precessional motion until the rotating assembly begins to tip over.

6.3.5. Accident Sequence SBF-5: {SBF $\cap$ UTP $\cap$ MSD $\cap$ SD}. In this accident sequence, the shaft bolts shear after a spindle-shaft seizure (**SBF**) but the unattached face-plate-fixture assembly continues to spin without appreciable precessional motion or wobble (**UTP**). The drive motor is shut off by the vibration detection system (**MSD**) and the rotating assembly consisting of the face plate, fixture and RV decelerates in an upright position atop the DBM (**SD**).

UTP: Under ideal circumstances, the face plate would continue to spin atop the spindle shaft. The spindle shaft fits into a recess in the bottom of the face plate. This recess could provide enough lateral stability to keep the spinning assembly upright or nearly so. The spinning assembly may experience relatively uniform friction at the contact between the face plate and shaft end. Gyroscopic motion of the spinning assembly could then continue until the assembly eventually came to rest. As the assembly slowed down, it might eventually tip until constrained by the contact between the bearing plate and face plate extension.

6.3.6. Accident Sequence SBF-6: {SBF $\cap$ UTP $\cap$ MSD $\cap$ CS}. This accident sequence is identical to SBF-5 except that the drive motor does not shut off (**MSD**) and continues to drive the rotating assembly intermittently (**CS**).

6.3.7. Accident Sequence SBF-7: {SBF $\cap$ UTP $\cap$ CPA $\cap$ PVE $\cap$ SFF}. In this accident sequence, the shaft bolts shear after a spindle-shaft seizure (SBF) and the unattached face-plate/fixture assembly begins precessional motion and wobble (UTP). This motion is not constrained by the bearing plate and decking sufficiently (CPA) to prevent tip over of the rotating assembly (PVE) with subsequent consequences as outlined above when a rotating assembly tips and falls to the DBM deck or floor (SFF).

6.3.8. Summary of Shaft-Bolt Shear Accident Sequences. Shearing of the shaft bolts because of spindle-shaft seizure could result in two distinct types of motion with differing accident consequences. If all other components in the torsional train from the spindle shaft to the fixture survive the spindle-shaft seizure and one or more shaft bolts survive, then the fixture will be arrested by the spindle-shaft seizure without impact of the RV on any stationary objects in the bay. If no shaft bolts survive the initial deceleration transient, then a rotating assembly consisting of the face plate, fixture and RV could spin like a top until coming to rest on the bearing plate. Alternately, the RV could be ejected from the rotating assembly during precession and nutation of the rotating assembly while spinning. The entire rotating assembly could also rip up the balancer decking and "walk-off" or tumble off to the bay floor still spinning at near its original angular velocity.

6.4. Spindle-Shaft Shear

Failure of the spindle shaft would result in accident progressions similar to those of failure of the shaft bolts. The shaft would fail above the point where seizure occurred. If the shaft failed inside the bearing housing, then the stub of the shaft still attached to the face plate would provide considerable stability to the spinning assembly, and the assembly would have a good chance of remaining upright as it decelerated. If the shaft broke just above the housing, the result would be nearly identical to that of shaft-bolt failure. However, in this case, precession would be almost certain to occur immediately because the face plate would not be supported on the shaft, as was the case for shaft bolt shearing. The accident is shown in Fig. 13. In this picture, ω is the angular velocity of the fixture/RV/face-plate assembly about its longitudinal axis, θ is the angle of precessional motion, and α is the precessional angular velocity about the original axis of rotation of the fixture-RV system. This figure shows how the face-plate extensions limit the tilt of the fixture/RV/face-plate assembly when they encounter the lower side of the decking and upper surface of the bearing plate.

The CCD for spindle-shaft shear is shown in Fig. 14. This CCD is virtually identical to the one for shaft-bolt shear. The accident sequences from this CCD are summarized in Table 6, which also has the same format as Table 3.

Fig. 13. Geometric model for spindle-shaft shear.

Fig. 14. Spindle-shaft shear cause-consequence diagram.

Table 6
Summary of Shaft-Shear Accident Sequences

Event Sequence	Branch Operators					Consequence	
Event Sequence	SSS	UTP	CPA	PVE	MSD	Outcome	Effect
1	N					FA	OK
2	Y	Y	Y		Y	SD	OK
3	Y	Y	Y		N	CS	
4	Y	Y	N	Y		RVE	
5	Y	N			Y	SD	OK
6	Y	N			N	CS	
7	Y	Y	N	N		SFF	

6.5. Summary of Accident Sequences

The accident sequences developed for the four types of accidents described above can be summarized by the condition of the RV when it leaves the balancing machine. A number of the accident sequences end with the RV decelerating in a stable configuration on the balancing machine because of friction. Other accident sequences end with the RV leaving the balancing machine with translational and axial angular velocities. These accident sequences can be classed by the outcome shown in the CCD tables, which is essentially a condition of the RV when it leaves the balancing machine. This classification is summarized in Table 7, where the maximum translational and angular velocities for the RV as estimated by our idealized calculations are given. In this table, ω is the original angular velocity of the DBM before the spindle shaft seizure, and a is the fixture radius. The entry "Low" indicates a value that is difficult to estimate using simple methods but is much lower than the other values in the table.

The CS outcome, although not shown as OK in our accident-sequence tables, is not included in this summary table. The CS outcome represents continued driving of an unattached fixture by the drive belt, which is attached to the face plate. This is an unstable condition, but not an accident condition until something happens to lead the accident progression to one of the undesirable paths on the CCDs.

7.0. CONCLUSIONS

This report documents the systematic analysis of possible accident sequences leading to RV impact on a stationary object because of spindle-shaft seizure on the Schenck dynamic balancing machine. The analysis used fault trees, FMEAs, and CCA to develop accident sequences that include causes of spindle-shaft seizure, physical development of the accident progression, and the possible modes of RV motion, each of which implies different modes of impact for the RV on stationary objects in the mass properties bay.

As a result of this analysis, insights have been gained concerning the spindle-shaft seizure accidents. Shaft seizure could result from a number of component or system faults, including a number of oil system faults that were apparently anticipated by the machine designers, because they have included some systems

Table 7
Summary of Accident-Sequence Outcomes

Accident Sequence Outcome	Maximum RV Translational Velocity	Maximum RV Axial Angular Velocity
Spinning fixture falls from the balancing machine (SFF)	Low	ω
Fixture released from rotation about a surviving bolt (FFO)	$1/2\omega a$	ω
Fixture strikes the alignment pole (IAP)	$1/2\omega a$	ω
RV Ejected from a precessing fixture (RVE)	Low	ω
RV ejected from a fixture rotating about a surviving bolt (RVE)	$1/2\omega a$	ω

and controls for oil system faults. Note that the presence of these controls would be expected to reduce the likelihood of many of these accidents. The occurrence of an over-speed condition could exacerbate a shaft seizure. However, such a condition would require faults in several controls and protective systems. Another exacerbating condition would be a significant error in the installation of any of the bolt sets during assembly of the machine or the fixture or attaching the fixture to the machine. Based on human reliability experience, this human error event could occur with a probability of from 0.1 to 10^{-4} per opportunity depending on the controls and ergonomics of the assembly procedure.⁹ A more exact estimate of the likelihood of improper assembly would require a human reliability analysis based on the specific procedures and work practices used. Exacerbating conditions on the bolts would be relatively uncommon in conjunction with a spindle seizure.

Some analysts consider the most likely failure mode from shaft seizure in the rotating assembly to be the shearing of the shaft-bolt set.⁸ Most of the accident sequences for shaft-bolt failure do not result in RV impact. The RV impact modes that can result in shaft-bolt failure are RV ejection (consequence RVE) and a spinning fixture fall from the balancing machine (consequence SFF). The RV ejection mode is unlikely because it relies on precessional motion to supply the centrifugal force for ejection. Precessional velocities for the fixture are such that ejection would require quite a large inclination angle. The inclination angle of the fixture is constrained in the case of shaft-bolt failure by the decking and bearing plate. The bearing plate and decking also constrain the "walking" of the spinning fixture-face-plate assembly for shaft bolt shearing.

Shearing of the face-plate bolts presents several RV impact modes. The most likely mode would be for a spinning fixture to walk across the decking and fall from the dynamic balancing machine (consequence SFF). RV ejection (consequence RVE) or fixture fly-off (consequence FFO) could occur if one face-plate bolt survives. However, single-bolt survival either places great strength demands on the surviving bolt or requires a relatively close match between rotating energy and the energy required to shear all the bolts and seems intuitively less likely than shearing of a few, none, or all bolts.

The results of the analysis can be summarized as follows.

- Shaft seizure may result from a number of causes, such as a severe load imbalance, failure of an axial bearing, failure of a radial bearing, failure of a bearing housing seal, or a primary shearing failure of the spindle shaft.
- A significant over-speed condition on the DBM at the time of accident initiation would increase the probability of loss of control of the RV and exacerbate the consequences of the accident by increasing the energy of the RV when impacting a stationary object in the bay. The speed controls and protective features for the DBM appear to be highly redundant and diverse, and no obvious common cause could be identified.
- Improper attachment of the fixture containing the RV to the DBM or improper assembly of the fixture could significantly increase the probability of an accident if a spindle shaft seizure does occur. These conditions could result from human error in selection of bolts, improper installation of bolts, or wear/aging of equipment (including cracking of fixture welds or components). Although the bolt sets are redundant, a significant potential for common-cause faults that affect all the bolts in a set is present because of the human error.
- If spindle shaft seizure does occur, several DBM accident conditions can result.
 - The fixture and RV remain attached to the DBM and are arrested in their motion.
 - The spindle shaft or all the shaft bolts completely shear, and the fixture/RV/face-plate system continues to rotate.
 - All the face-plate bolts shear and the unattached fixture continues to rotate.
 - All but one of the face-plate bolts shear, and the fixture begins to rotate about the surviving bolt.
 - The fixture structure fails, and the unattached RV (possibly along with some part of the fixture) continues to rotate.
- As a result of these DBM accident conditions, the subsequent RV motion can include the following.

- The RV remains in the attached fixture and decelerates in a stable configuration because of friction with the fixture mountings.
- The unattached fixture/RV/face-plate system continues to spin undergoing precessional motion but constrained in the angle of inclination by the decking and bearing plate of the DBM. The eventually RV comes to rest still in the fixture, which is more or less upright on the DBM.
- The unattached fixture/RV system begins unconstrained precessional motion and "walks" off the DBM decking. The fixture/RV system falls to the bay floor still spinning and rolls or tumbles across the bay floor.
- The fixture/RV system continues to rotate about a single face-plate bolt until the RV and fixture eventually come to rest, still attached to the single face-plate bolt
- The fixture/RV system rotates about the single surviving bolt until it impacts the alignment pole.
- The fixture/RV system rotates about the surviving bolt until the bolt breaks and the fixture/RV system flies off the DBM with both translational and rotational motion.
- The RV is ejected from the fixture during precessional motion or rotation about a single face-plate bolt.

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APPENDIX A

REENTRY VEHICLE IMPACT FAULT TREE

The RV impact fault tree is shown in Fig. A-1. This fault tree was developed to determine which of the possible RV impact modes could be caused by spindle-shaft seizure. It also shows what other accident-initiating events are comparable to spindle-shaft seizure in their effect. We developed the fault tree only to the point where rapid deceleration of the rotating assembly appears as an event because spindle-shaft seizure is a recognized antecedent cause of rapid deceleration. The cut sets of this fault tree are discrete event approximations of sequences of events leading to RV impact on a stationary object during dynamic balancing.

Fig. A-1. Reentry vehicle impact fault tree (1 of 6).

Fig. A-1. Reentry vehicle impact fault tree (2 of 6).

Fig. A-1. Reentry vehicle impact fault tree (4 of 6).

Fig. A-1. Reentry vehicle impact fault tree (5 of 6).

Fig. A-1. Reentry vehicle impact fault tree (6 of 6).

APPENDIX B

BOLT-SHEAR FAULT TREE

We developed a fault tree (Fig. B-1) to qualitatively enumerate the possible combinations of bolt and installation faults that could contribute to bolt failure. This fault tree is for exploratory purposes only and would need careful handling to produce quantitative probability estimates of bolt-failure probability. The fault tree was constructed in this way to prevent a combinatorial explosion of possibilities. The cut sets of this fault tree show the different possible combinations of bolt faults and installation errors that could occur. The event that one or more bolts fail given a spindle-shaft seizure is the basic event "Deceleration" in the tree. The probability of this event will be different for each different cut set of the tree. If a different event had been used to represent failure of the bolts for each possible combination of installation and bolt conditions, the tree would have been much larger and more difficult to understand. Thus, we used the simplified form.

Fig. B-1. Bolt-shear fault tree (1 of 2).

Fig. B-1. Bolt-shear fault tree (2 of 2).

APPENDIX C

SPINDLE-SHAFT SEIZURE FAULT TREE

A fault tree for the hydraulic spindle-shaft seizure event is shown in Fig. C-1. This fault tree was developed to the level of component or subsystem failures and human actions. The cut sets of this fault tree are discrete event models of sequences of events that lead to spindle-shaft seizure. The fault tree includes control or safety functions that could arrest a developing accident's progression.

Fig. C-1. Spindle-shaft seizure fault tree (1 of 9).

Fig. C-1. Spindle-shaft seizure fault tree (2 of 9).

Fig. C-1. Spindle-shaft seizure fault tree (3 of 9).

Fig. C-1. Spindle-shaft seizure fault tree (4 of 9).

Fig. C-1. Spindle-shaft seizure fault tree (5 of 9).

Fig. C-1. Spindle-shaft seizure fault tree (6 of 9).

Fig. C-1. Spindle-shaft seizure fault tree (7 of 9).

Fig. C-1. Spindle-shaft seizure fault tree (8 of 9).

Fig. C-1. Spindle-shaft seizure fault tree (9 of 9).

APPENDIX D

AN INTRODUCTION TO CAUSE-CONSEQUENCE DIAGRAMS

CCDs graphically describe the development of accident sequences from initiating events to consequences using logic symbols connected by arrows that indicate the flow of events. These logic symbols provide more flexibility and power in capturing the complexities of an accident sequence in which physical phenomena play an important role in accident progression. One advantage of the CCD over some other graphical representations of accident progression, such as the event tree, is the ease with which CCDs typically are understood by engineers. In addition, the CCDs allow more flexibility in representing complex accident progression because of the greater number of available symbols.

A CCD is made up of logic symbols connected by arrows called *directors*, which indicate the direction of event flow in the CCD and only connect symbols that influence each other. Loops generally are not allowed in a CCD. In mathematical terms, a CCD is an acyclic, directed graph. The logic symbols used in CCDs are shown in Fig. D-1. The following paragraphs describe each symbol used in the CCD.

Consequence Descriptor. Consequence descriptors are the terminal points of all CCD paths. The consequence descriptors contain descriptions of the final state reached by following a path through the CCD from the initiating event through all the logic symbols. Multiple directors may enter one consequence descriptor, but no director may exit one.

Branching Operator. CCDs have a binary logical structure. Branching operators indicate where alternative paths could be followed in an accident progression, depending on the conditions encountered at that point in the accident. The text of the branching operator describes an event or condition. If the event occurs or the conditions are met, a director is followed from the "Yes" branch of the operator. Other wise, the director from the "No" branch is followed. Each branching operator can have multiple input directors but can have only two outgoing directors, one each from the "Yes" and "No" branches.

Initiating Event. The initiating-event symbol is the starting point for a CCD. It shows the event that leads to the consequences developed in the rest of the diagram. The initiating-event symbol can serve as an attachment point for a fault tree that develops the causes of the initiating event. Multiple directors may exit a single initiating-event symbol. No directors enter it.

Time-Delay Operator. The time-delay operator provides a way to describe the time dependency in an accident progression. For example, a time delay can be placed in an accident progression path to illustrate the heat-up time before a component fails. The time-delay operator is one of the symbols that allows the CCD to capture complicated accident progressions more easily than an event tree

Event Descriptor. Event descriptors also enhance the flexibility of the CCD and allow complex accident sequences to be described easily. The event descriptor is placed at the side of a director and indicates an intermediate condition for the system during an accident progression. These symbols are useful in capturing the development of an accident because of physical phenomena that occur in sequence as a result of antecedent events and conditions, which are represented in logic symbols occurring upstream in the event flow of the CCD.

Continuation. The continuation symbol is used to show alternate paths for a single initiating event that are on another page of the diagram.

Transfer. The transfer symbol is used to show either a repeated structure or a structure that is on another page of the diagram.

Accident sequences can be generated on a CCD by following a set of directors from the initiating event through all the branching operators encountered until a consequence descriptor is encountered. This process is repeated until all the possible paths have been traced. The number of paths is at least equal to the number of junctions of directors and consequence descriptors. If directors overlap, as in the spindle-shaft CCD, there will be more paths than director-consequence descriptor junctions.

Consequence Descriptor

Branching Operator

Initiating Event

Time Delay Operator

Event Descriptor

Continuation

Transfer

Fig. D-1. Symbols used in cause-consequence diagrams.

APPENDIX E

REENTRY VEHICLE EJECTION PHENOMENA

1.0. INTRODUCTION

We used the simple mechanics of solid bodies to investigate the conditions under which an RV could be ejected from a rotating fixture. This analysis is not intended to provide detailed predictions of the RV motion during the accident progression but rather to help delineate accident progression possibilities based on physical considerations and to help determine what parameters affect the likelihood of RV ejection for different accident sequences.

In this analysis, we assumed that the face-plate bolts are located near the circumference of the lower fixture flange and that the RV may be approximated by a cone. The RV is restrained along the direction of the fixture-RV longitudinal axis by a ring. This restraint is adequate during normal operation because the fixture-RV system normally rotates about a longitudinal axis that passes through the center of mass. During precessional motion of the fixture-RV system or rotation of the system about a single bolt, the system's center of mass will experience forces that will tend to eject a conical RV even if the fixture is upright. Inclining the longitudinal axis of the system to the axis of rotation because of precession of an unattached fixture or bending of a single surviving bolt will increase the forces tending to eject the RV. A simple analysis of RV ejection in upright and inclined situations is presented here to demonstrate the phenomena involved and approximate conditions for which RV ejection could occur.

2.0. INITIATION OF REENTRY VEHICLE EJECTION FROM AN UPRIGHT FIXTURE ROTATING ABOUT A SURVIVING BOLT

The conical shape of the RV will affect the angle at which it is ejected for a given angular velocity of the center of mass. This can be seen by considering a mass on an inclined plane at angle γ as in Fig. E-1. In this idealized situation, the mass lies on a frictionless surface. A force, F_c , acts on the mass in the horizontal direction, representing centrifugal force from rotation around the axis of rotation shown. Because of the incline of the surface, a component of this horizontal force, F_e , will act up the plane. When this force is larger than the component of the gravitational force down the plane, F_r , the mass will accelerate up the plane. The force component, F_e , will have magnitude $F_c \cos \gamma$, and the force component, F_r , will have magnitude $mg \sin \gamma$. The two forces also will have a component, F_n , normal to the plane surface with magnitude $mg \cos \gamma + F_c \sin \gamma$.

If the RV were a cylinder resting in a fixture contoured to hold it vertically, then the fixture would have to tip for the RV to experience ejecting forces. For an idealized conical RV resting in a fixture contoured to support it, the RV center of mass will experience an ejecting force parallel to the surface of the cone even if the fixture is upright. In the actual situation, friction, the limited extent of the contoured support surfaces, and the radial displacement of the RV center of mass from the axis of rotation as it moves up the fixture will complicate the motion considerably, but the simple analysis discussed below gives some idea of the possible RV motions and their relative importance.

Fig. E-1. Centrifugal force up an inclined plane.

The forces acting on an idealized spinning or stationary RV in a frictionless fixture with surfaces contoured to fit the RV conical shape are shown in Fig. E-2. The fixture longitudinal axis is rotating around a vertical z axis through one edge with angular velocity ϕ . The half-angle of the cone apex is γ (note that here the angle γ differs from that in Fig. E-1 by $\pi/2$). The force, F_e , is a component of the centrifugal force, F_c that acts along a direction parallel to the surface of the RV cone. This component is given by

$$F_e = m\phi^2 a \sin \gamma .$$

The force acting opposite to this ejecting force is a component of gravity given by

$$F_{rg} = mg \cos \gamma$$

and the restraining force exerted by the restraining ring, represented by mgq in our model. An equilibrium between these forces is achieved when the angular velocity is

$$\phi = \sqrt{\frac{g(\cos \gamma + q)}{a \sin \gamma}} , \quad (E-1)$$

Fig. E-2. Conical RV ejection from fixture rotating about a bolt.

Equation (E-1) is plotted in Fig. E-3. For values of $\gamma = 15$, $a = \frac{1}{2}$ m, and $q = 5$ (restraining force of 5 g's), the angular velocity at equilibrium is about 200 rpm. An over-speed condition for the balancing machine would be required to reach this rotational velocity around a surviving single face-plate bolt.

3.0. CONDITIONS UNDER WHICH REENTRY VEHICLE EJECTION PROGRESSES

If the angular velocity exceeds the equilibrium value, then the RV will overcome the restraints and begin to move out of the fixture. We assume that when the RV starts to move, it breaks the restraining ring, and the restraining force drops to the maximum for friction alone ($q = \mu F_n$). At this point, we need to examine the angular velocity at which the RV will leave the fixture. To do this, we refer to Fig. E-4. In this figure, the solid cone is the position of the spinning RV just before it loses contact with the fixture (shown by the rectangle). The dotted cone is the initial RV position and the surface of contact between the RV and the fixture.

Fig. E-3. RPM for initiating RV ejection from an upright fixture.

Fig. E-4. RV at point of ejection from the fixture.

As the RV moves out of the fixture, the radius of rotation of its center of mass about the bolt axis and the moment of inertia of the RV-fixture system will both increase. This will decrease the angular velocity of the system about the bolt axis. One might reasonably ask under what conditions RV ejection will continue as the RV moves out from its original position. For example, we can estimate the magnitude of the restraining force coefficient, q , that will ensure that after ejection motion is started by overcoming the restraining force, it will continue (resisted now only by friction) until the RV leaves the fixture.

We can get some ideas about this question by idealizing the problem and invoking the conservation of energy of the system in a manner analogous to that used in Appendix F. By doing so, we can estimate the change in angular velocity of the RV-fixture system as the RV moves further from the axis of rotation. First, we assume that the RV and fixture maintain frictionless contact throughout so that the movement of the RV center of mass affects the entire system moment of inertia. We assume that this contact continues right up until the RV tip reaches the edge of the fixture. In reality, the RV will begin to tip and precess when its center of mass rises much above the top of the fixture, but we will ignore this effect, which will tend to result in RV ejection long before the RV reaches the position shown in our illustration. We have chosen the illustrated RV position because it is the most demanding in terms of the angular velocity required to keep ejection motion going. When the RV tip reaches the last point of contact with the fixture, the radius of the center of mass around the bolt axis will be $2a$ as in Fig. E-4. An energy balance between the rotational energy before ejection begins, denoted with subscript i , and at the point of last contact, denoted with subscripts f , is

$$I_f \phi_i^2 + m_{RV} a^2 \phi_i^2 + I_{RV} \omega^2 = I_f \phi_f^2 + m_{RV} 4a^2 \phi_f^2 + I_{RV} \omega^2 ,$$

where ϕ_f and ϕ_i are the initial and final angular velocities of the RV-fixture system around the bolt and $I_{RV}\omega^2$ is the energy of rotation of the RV about its longitudinal axis. Solving for ϕ_f ,

$$\phi_f = \phi_i \sqrt{\frac{I_f + m_{RV} a^2}{I_f + 4m_{RV} a^2}} .$$

Substituting in the value of $3/2 m_f a^2$ for I_f and recognizing that the masses of the fixture and RV are comparable, we get

$$\phi_f \approx \phi_i \sqrt{\frac{5}{11}} . \quad (E-2)$$

Now for ejection to continue at the point of last contact, Eq. (E-1) must be satisfied with the value a replaced by $2a$. Thus,

$$\phi_f \approx \phi_i \sqrt{\frac{5}{11}} \geq \sqrt{\frac{g(\cos \gamma + q_f)}{2a \sin \gamma}} . \quad (E-3)$$

However, we know that for ejection to have started, ϕ_i must satisfy Eq. (E-1) as well. Replacing ϕ_i in Eq. (E-3) with Eq. (E-1) and q_f with an expression for μF_n and solving for q_i gives

$$q_i \geq \frac{\cos \gamma}{10} + \frac{11}{10} q_f = \frac{10\mu + 1}{11} \cos \gamma + \frac{10\mu \phi_f^2 a \sin \gamma}{11g} \approx 1 + 1.1 q_f .$$

Thus, the restraining force does not have to be much larger than the frictional force to ensure that when the restraining force is overcome, RV ejection will continue until the RV leaves the fixture.

4.0. INITIATION OF REENTRY VEHICLE EJECTION FROM A DETACHED FIXTURE IN PRECESSIONAL MOTION

Ejection can occur at lower angular velocities if the fixture is inclined at an angle to the vertical. Precession of the fixture about a vertical axis and rotation about a bending bolt are the two situations examined in this study that can increase the probability of RV ejection. The reader should refer to Fig. E-5 for the following discussion of precessional RV ejection. In this figure, the fixture is represented by the black box, and the RV is represented by the red cone. The fixture-RV system is shown as rotating with angular velocity of magnitude ω about its longitudinal axis. This axis is at an angle θ to the vertical. The axis of rotation of the cone is precessing at angular velocity of magnitude ϕ about the vertical axis. In this analysis, we ignored the effect of nutation, or wobble, and for simplicity assumed at least quasi-steady precession. The force F_c is the component of the centrifugal force acting on the RV center of mass along the RV longitudinal axis generated by precessional rotation. The force, F_r , is the restraining force component acting in the opposite direction to F_c along the same axis. The restraining force includes a gravitational force component and a restraining force component exerted by the restraining ring at the top of the fixture. The RV will be ejected when $F_c > F_r$.

The component of the centrifugal force of magnitude $m\phi^2 a$ along a line through the center of mass parallel to the RV edge is

$$F_e = m\phi^2 r \sin(\theta + \gamma) .$$

The radius of the center-of-mass motion is

$$r = h \sin \theta .$$

Therefore, the centrifugal force component is

$$F_e = m\phi^2 h \sin(\theta + \gamma) \sin \theta .$$

The total force resisting the centrifugal force is termed F_r in our model. This force is the sum of the gravitational force, mg , and a mechanical restraining force exerted by a restraining mechanism acting along the system axis. If we assume the restraining force is of the form mgq , where q is some positive real number, then

$$F_r = mg(q + \cos(\theta + \gamma)) .$$

The balance of forces on the RV center of mass then is stated as

$$\frac{F_e}{F_r} = \frac{\phi^2 h \sin(\theta + \gamma) \sin \theta}{g(q + \cos(\theta + \gamma))} .$$

In general, the precessional velocity, ϕ , will be much smaller than the rotational velocity, ω ; therefore, ejection from precession will be of relatively little concern.

A numerical example of precessional rotation is shown in Fig. E-6. This figure shows a plot of the ratio of the centrifugal force to the restraining force on the RV during precessional motion minus the value 1. Thus, the forces are in balance when the ordinate is 0, and positive values of the ordinate indicate that RV ejection will occur. In the case illustrated, the height of the RV center of mass, h , is 1 m; the precessional angular velocity is 100 rpm (quite a high value for the rotational speed anticipated for the balancing machine); the half-conical apex angle is 15° ; and the restraining force is 5 times the weight of the RV. According to the model developed here, if the fixture tipped to over 40° , RV ejection could occur for these parameters. This indicates that ejection of an RV from a precessing fixture would not be very likely unless the fixture were in the process of tipping over on its side.

Fig. E-5. Schematic for precessional RV ejection.

Fig. E-6. Example of precessional RV ejection.

5.0. INITIATION OF REENTRY VEHICLE EJECTION FROM A FIXTURE ROTATING ABOUT A BENDING SURVIVING BOLT

When a single face-plate bolt survives and becomes the axis of rotation for the fixture-RV system, the situation can be described by Fig. E-7. Note that the bolt has bent and stretched, so the fixture-RV system longitudinal axis is at an angle θ with the vertical. In this case, the centrifugal force component is generated by rotation about the surviving bolt at angular velocity of magnitude ω . The centrifugal force component parallel to the RV cone edge tending to eject the RV is given by

$$F_e = m\omega^2 r \sin \psi = m\omega^2 r \sin(\theta + \gamma) .$$

However, the radius of rotational motion now is given by

$$r = \sqrt{h^2 + a^2} \sin(\theta + \alpha)$$

because the center of mass of the system is rotating about the bolt and is not precessing about the vertical. Thus, the centrifugal force component is

$$F_e = m\omega^2 \sqrt{h^2 + a^2} \sin(\theta + \alpha) \sin(\theta + \gamma) .$$

As before, the restraining force component is

$$F_r = mg(q + \cos(\theta + \gamma)) .$$

Thus, the ratio of the centrifugal to restraining force is

$$\frac{F_e}{F_r} = \frac{\omega^2 \sqrt{h^2 + a^2} \sin(\theta + \alpha) \sin(\theta + \gamma)}{g(q + \cos(\theta + \gamma))} .$$

Fig. E-7. Schematic for surviving bolt rotation RV ejection.

An example calculation for rotational ejection is shown in Fig. E-8. This figure shows a plot of the ratio of the centrifugal force to the restraining force on the RV during rotation about a surviving bolt minus the value 1. Thus, the forces are in balance when the ordinate is 0. Positive values of the ordinate indicate that RV ejection will occur. In the case shown, the height of the RV center of mass is 1 m, the radius of the fixture 1/2 m, the rotational angular velocity is 140 rpm, the half-conical apex angle is 15°, and the restraining force is 5 times the weight of the RV. These values are all reasonably representative for the balancing machine assuming that the initial balancing machine speed was about 275 rpm. According to the model developed here, if the fixture was tilted to about 8° by bolt bending and stretching, RV ejection could occur for these parameters. This indicates that in the unlikely event that the fixture-RV begins to rotate around a surviving bolt, RV ejection is a definite possibility, especially in an over-speed condition.

Fig. E-8. Rotational RV ejection example.

6.0. SUMMARY

Based on the simple analysis in this appendix, RV ejection would appear to be of most concern if the fixture is able to start rotating around a surviving bolt. Precessional angular velocities and the radius of rotation of the center of mass are too small for ejection during precession until the fixture begins to tip over. RV ejection with the fixture rotating about a surviving bolt is more likely because of higher angular velocities and larger radii of rotation. The conical shape of the contact between the RV and fixture reduces the angular velocity at which RV ejection will occur, with a larger conical apex angle leading to lower ejection angular velocities. For sufficiently high rotational velocities, ejection with the fixture upright is possible. However, any ejection in the actual system is likely to be a very complex motion because the contact between the RV and fixture is not continuous but is restricted to a few points, thus introducing the possibility of torque during ejection with complex tumbling motion occurring as a result.

APPENDIX F

ROTATION AROUND A SURVIVING FACE-PLATE BOLT

1.0. INTRODUCTION

We used simple mechanical principles to obtain an idea of the maximum rotational velocity that can be achieved by stopping the axial rotation of the fixture-RV system and redirecting that rotational energy into rotation about a bolt. We assumed that the bolts that attach the fixture to the face plate are located near the circumference of the lower flange of the fixture. If the reaction is totally elastic, kinetic energy is conserved, and the bolt acts like an ideal spring, then we can find an upper bound on the final rotational energy by equating the initial and final kinetic energies of the system.

2.0. ROTATION WHEN THE REENTRY VEHICLE AND FIXTURE ARE RIGIDLY ATTACHED TO EACH OTHER

The initial kinetic energy of the system rotating about the vertical z axis at speed ω is given by

$$E_i = \frac{1}{2} I_z \omega^2 ,$$

where I_z is the moment of inertia of the system about the z axis. We approximate the RV as a solid right cone, and the fixture as a hollow right cylinder. For a cone, the moment of inertia around the longitudinal axis is

$$I_z = \frac{3}{10} m a^2 ,$$

whereas for a hollow cylinder it is

$$I_z = \frac{1}{2} m a^2 .$$

The moment of inertia for the fixture-RV system will be between these values.

When the spindle shaft seizes, rotation about the z axis is arrested. If all but one of the bolts holding the fixture-RV system are sheared, then the remaining bolt will absorb all the rotational energy of the system and stop rotation about the z axis. The torque applied by the bolt through its rigidity will start the system rotating about a vertical axis through the bolt. We first assume that the RV and fixture are rigidly attached. The RV then also will be arrested in its rotation about the z axis. As a maximum, assume that all the energy absorbed in the bolt when stopping the initial rotation is returned to the system in its new rotational configuration. In this new configuration, the energy is now

$$E_f = \frac{1}{2} I_f \alpha^2 ,$$

where I_f is the moment of inertia of the system around the new axis of rotation, which is now located near the edge of the fixture-RV-system. This new moment of inertia is given by the parallel axis theorem as

$$I_f = \frac{3}{10} m a^2 + m a^2 = \frac{13}{10} m a^2$$

for a cone and

$$I_f = \frac{1}{2} m a^2 + m a^2 = \frac{3}{2} m a^2$$

for a hollow cylinder. The geometry for applying the parallel axis theorem for moments of inertia is illustrated in Fig. F-1. Equating the initial and final energies gives us the relationship

$$\frac{\alpha}{\omega} = \sqrt{\frac{I_z}{I_f}}$$

The values are 0.48 for a cone and 0.58 for a cylinder. Thus, the maximum value of the rotational velocity after the change in rotational axis will be between these two values.

Fig. F-1. Geometric relationship of initial and final axes of rotation for single-surviving-bolt scenario.

3.0. ROTATION WHEN THE REENTRY VEHICLE IS NOT RIGIDLY ATTACHED TO THE FIXTURE

If the fixture and RV are not rigidly attached (a situation closer to the actual one), then only the fixture will be stopped in its rotation by the surviving bolt. The RV can continue to rotate with its initial rotational velocity about its z axis. However, when the rotational energy of the fixture is returned to the system, it will be used in accelerating the entire system around the surviving bolt. Thus, the fixture and RV will be rotating around the bolt at velocity α , whereas the RV still will be spinning at velocity ω around its vertical axis. In this case, the initial energies of the fixture and RV are

$$E_{fi} = \frac{1}{2} I_{fi} \omega^2 \quad \text{and}$$

$$E_{Rvi} = \frac{1}{2} I_{RVz} \omega^2 ,$$

where I_{fi} and I_{RVz} are the moments of inertia for the fixture and RV. The moment of inertia, I_{fi} , is given by

$$I_{fi} = \frac{1}{2} m_f a^2 ,$$

where m_f is the fixture mass and a is the fixture radius.

As an idealization, let us assume that only the fixture energy is absorbed by the bolt. The RV continues spinning inside the fixture at its original rate as the fixture starts to rotate around the bolt. The fixture will exert forces on the surface of the RV where the RV cone contacts the fixture. If we ignore friction between the spinning RV and the fixture, then all of the forces will be normal to the RV and pass through the vertical axis of the RV cone. The resultant force vectors will exert a centripetal force on the RV center of mass without exerting any torque on the RV. Thus, the RV will move about the bolt like a point mass concentrated at the center of mass with an energy of $\frac{1}{2}m_{RV}a^2\alpha$.

The final energy of rotation about the bolt includes the rotational energy of the fixture about the bolt, E_{fbolt} ; the rotational energy of the RV about its longitudinal axis, E_{RVf} ; and the rotational energy of the RV about the bolt, E_{RVbolt} . These energies are given by

$$E_{fbolt} = \frac{1}{2}I_z\alpha^2 ,$$

$$E_{RVf} = \frac{1}{2}I_{RVz}\omega^2 ,$$

and

$$E_{RVbolt} = \frac{1}{2}m_{RV}a^2\omega^2 .$$

Equating initial and final energies and solving for the ratio of the initial angular velocity of the system around its vertical axis to the final angular velocity around the bolt we get

$$\frac{\alpha}{\omega} = \sqrt{\frac{I_{fz}}{I_f + m_{RV}a^2}} = \sqrt{\frac{\frac{1}{2}m_f a^2}{\frac{3}{2}m_f a^2 + m_{RV}a^2}} = \sqrt{\frac{m_f}{3m_f + 2m_{RV}}} .$$

The mass of the fixture is only about the same as the mass of the RV, so the ratio of the final rotational velocity to the initial rotational velocity will be of the order of 0.45.

These simple calculations indicate that in the unlikely event that the fixture starts to rotate around a surviving bolt, the angular velocity of the fixture-RV system probably will be less than $\frac{1}{2}$ of the balancing machine angular velocity.

4.0. SUMMARY

Under ideal conditions, a single bolt could survive the spindle-shaft event and become the axis of rotation for the fixture. This is a particularly undesirable condition because the center of mass of the RV-fixture system is now rotating around an axis. Based on conservation of kinetic energy and changes in the moment of inertia for the rotating masses brought about by the change in axis of rotation, the angular velocity of the system around the bolt could be as much as $\frac{1}{2}$ the original angular velocity of the fixture-RV system about its longitudinal axis. However, a single bolt would be very unlikely to survive. Such a scenario either requires one super-bolt or absorption of almost all the rotational energy in shearing the other bolts so that the surviving bolt is not over-stressed. In the latter case, the rotational energy of the fixture-RV system about the bolt would be much less than the maximum based on elastic redirection of the rotation as assumed in the simple calculation in this appendix.

APPENDIX G

PROBABILITY OF IMPACT WITH POLE FOR SINGLE-SURVIVING-BOLT SCENARIO

In this appendix, we derive an approximate expression for the probability that the surviving bolt will be positioned such that the rotating fixture will strike the alignment pole. This probability expression is based on the geometric construction shown in Fig. G-1. We assume that all of the possible positions where the surviving bolt may be located are on a circle, called the bolt circle, with the radius of the fixture, R , drawn about the center of the face plate located a point C_2 . We assume that the face plate has equal probability of coming to rest with the surviving bolt at any of these positions. To strike the alignment pole at its point of closest approach to the face plate indicated by point C_1 , the face-plate bolt must be located within the diameter of the fixture from the alignment pole closest approach, a distance of $2R$. Thus, we draw a circle of radius $2R$ around the alignment pole point at C_1 , which is located a distance d from the edge of the bolt circle and a distance $R + d$ from the center of the bolt circle at C_2 . This circle intersects the bolt circle of possible bolt positions at I_1 and I_2 . All the points on the bolt circle between these two points are close enough to the alignment pole for the fixture to strike the pole when it rotates around the bolt.

The probability that the bolt will come to rest in the zone where the fixture will strike the pole is just the fraction of the bolt circle circumference between I_1 and I_2 . This fraction is given by the ratio of the angle subtended by the sector of the circle between I_1 and I_2 divided by 2π . The half-angle ψ of the sector may be found by the cosine rule for oblique triangles. Using this rule, the angle ψ can be found from the three sides of the triangle (C_1, C_2, I_1):

Fig. G-1. Geometric figure for calculating arc angle for single-surviving-bolt impact.

$$4R^2 = R^2 + (R + d)^2 - 2R(R + d)\cos\psi .$$

Expressing d as a product of a fraction μ and R , we get

$$4R^2 = R^2 + R^2(1 + \mu)^2 - 2R^2(1 + \mu)\cos\psi .$$

Solving for ψ , we get

$$\psi = \text{ArcCos} \left[\frac{(1+\mu)^2 - 3}{2(1+\mu)} \right]$$

The probability of striking the pole is the ratio of points on the smaller circle that result in a pole strike to the total number of points. This can be found by comparing the arc of points resulting in a strike with the total circumference. The arc of points that serves as a rotation point for the fixture and results in a pole strike is 2ψ . The entire bolt circle subtends an angle 2π . Thus, the probability of striking the pole during rotation about a single surviving bolt is ψ/π .

A plot of the probability vs the distance of the pole from the bolt circle edge as a fraction μ of the face-plate radius R is shown in Fig. G-2. The alignment pole is a fixed distance of a few inches from the edge of the face plate. Thus, the size of the fixture relative to the face-plate diameter is important in determining the probability of a rotating fixture striking the alignment pole. In the mass properties bay, the fixture diameter is close to that of the face plate and the fractional distance from the alignment pole to the bolt circle edge is close to 1. Under these circumstances, the probability of the fixture hitting the pole in the surviving bolt scenario is approximately 0.5 according to this simple model.

Fig. G-2. Probability of pole strike as a function of fractional distance from bolt circle to alignment pole center