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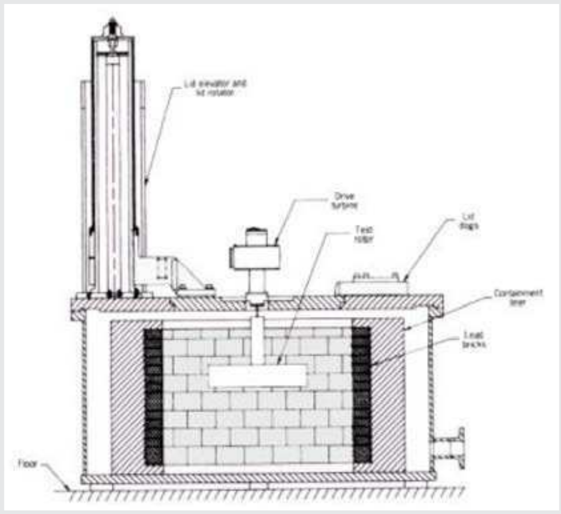
Ensuring Spin Test Safety

Every Spin Test System manufacturer has had a burst containment failure in their history where things went catastrophically wrong by releasing high energy burst fragments outside of the chamber. All of these failures resulted in at least a costly repair to the spin chamber. Tragically, one containment failure of a spin test system in Europe resulted in the loss of a life. In this case, personnel were operating the equipment close by when a burst sent uncontained fragments into the surrounding area. Eric Sonnichsen, founder and Chief Technology Officer of Test Devices, published the following article in December 1993 as a public service shortly after Test Devices' own containment failure caused him to analyze the issue of spin test safety. Recognizing the potential for additional destruction and injury in the spin test industry, Mr. Sonnichsen felt manufacturers and users should be aware of the dangers and learn from our collective lack of foresight in the hope of preventing future accidents. Following his safety review, Test Devices modified its own spin test systems, and those in the field. Test Devices also instituted strict policies prohibiting operators in a test cell while a test is in operation. Although the format is changed for the web, the following is an exact reprint of the article.

Because many of the hazards associated with centrifugal stress testing of rotation components (spin test systems) are not known, users must take precautions. The kinetic energy of typical turbo-machinery components is very high at burst speed, and the fragments of a disk can do serious damage to structures and people.



SPIN TEST SYSTEMS, which are used extensively in the turbomachinery industry for evaluating the centrifugal strength and fatigue life of high-speed rotating components such as turbine disks and centrifugal compressors, allow stress testing of high-speed components in a controlled environment. Therefore, these systems are faster and less expensive to use than testing in the target engine or machine.

Since the components tested are usually spun close to failure stress, centrifugal burst is sometimes a result. Spin test systems must be designed to contain the fragments of high-speed rotors at burst, protect the users from potential injury, and save the burst fragments intact for analysis if possible.

Fig. 1 — Spin Test Systems must be designed to contain the fragments of high-speed rotors at burst, protect users from potential injury, and save the burst fragments intact for analysis. Shown is a typical spin layout.

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Spin testing is dangerous. The kinetic energy of typical turbomachinery components is very high at burst speed, and the fragments of a disk can do serious damage to structures and people if containment is inadequate. For example, a steel disk 14 inches in diameter and 3 inches thick, spinning at 27,000 rpm has a kinetic energy of about 3 million Ib-ft, the equivalent of five full-size automobiles traveling together at 60 miles per hour. It is easy to understand why containment structures must be robust and well designed, able to withstand the impact of fragments of bursting disks.

The use of composites in a new generation of rotating parts designed to store large amounts of energy (like energy-storage flywheels) provides additional issues for spin pit safety. Since these parts store substantial energies in relatively small form factors (small size), spinning them in some existing spin pits may cause containment problems that did not previously exist. Additionally, composites generate large amounts of dust during a burst, which can ignite an explosion when an oxidizing agent and a spark arc present.

Many of the spin test systems in industrial use have been designed without full appreciation of the energies involved. As a result, several serious accidents have occurred but no injury or loss of life has been reported; however, this appears to be only the result of good fortune.

No published information detailing spin test equipment failures has been found, but a series of accidents has been reported during discussions with organizations that perform spin testing. The following descriptions of various actual incidents and potential dangerous situations illustrate some of the hazards that must be addressed in the design of a spin test facility or any assessment of the risks of operation.

The earliest accident reported occurred during the intentional overspeed burst of an aluminum-magnesium compressor about 30 years ago. The spin chamber was installed below ground, with the cover at floor level. The chamber cover was restrained by two sliding latches.

The bursting disk was surrounded by several concentric rings of aluminum, installed to absorb the burst energy of the disk and preserve the disk fragments.

When the burst occurred, the cover of the chamber was blown through the roof of the building, and is said to have made an additional hole next to the original when it re-entered. No injuries resulted.

An analysis of the accident revealed that the most likely cause was the ignition of aluminum or aluminum- magnesium dust or flakes, which were produced by the impact of the fragments of the burst disk against the surrounding aluminum rings. Although this test was conducted under vacuum, as is typical, air got into the chamber, apparently as a result of the failure of a glass sight disk installed in the cover.

The typical spin test system is designed with an air turbine drive mounted on the chamber cover, with a thin flexible shaft passing through an oil seal into the vacuum chamber. The article under test is suspended from this flexible shaft (“spindle”) inside the chamber, surrounded by a thick steel protective cylinder. The turbine, however, is outside the chamber and no burst protection is provided except for its structural casing. While there have been no reported incidents of drive turbine burst, such an event is certainly possible, and although the turbines are constructed with sufficient material surrounding the rotor to expect containment, no tests to demonstrate their effectiveness have been conducted.

Because the spindle passes into the chamber, it is subject to very high forces during a burst. Although these forces are nearly always transverse, resulting only in spindle fracture, there has been at least one incident where the axial forces during burst caused the high velocity ejection of the drive spindle. It was reported that the spindle impacted a steel beam above the test facility and left a deep impression in the beam (and possibly on the test operator as well). It should be noted that the turbine's top cover was not installed when the spindle ejection occurred.

Two accidents involving serious property damage have been reported. In the first instance, the accident was caused by the overspeed of a drive turbine as a result of a control system failure. A large welded centrifugal compressor wheel was being spun to maximum speed in a horizontal test rig: The drive steam valve failed to close when it reached the intended speed, and the wheel achieved burst speed. Since the burst containment cylinder was only a fraction of the appropriate thickness, the burst fragments escaped, causing major damage to the building and surrounding equipment. Remarkably, this accident occurred at shift change so that the machine operators who normally would have been in the area of destruction were out of the way and no injuries occurred.

The second reported case of containment failure occurred in a similar horizontal test machine of inadequate design. In this case, the burst occurred at test speed as a result of a flaw in the article under test. Major damage to the building resulted, but again there were no injuries. In this instance the bystanders were saved only by good fortune, since the high-velocity shrapnel narrowly missed hitting them.

In both of these accidents the test equipment had been in service for many years without incident, giving a highly misleading sense of security. Because the burst cylinder design thickness was insufficient to contain the rotor fragments, the first time a rotor burst, the containment failed.

Angular Momentum Transfer

The total angular momentum of a spinning disk is not changed when it bursts. This momentum is transferred to the containment structure by the impact of the burst fragments.

In a spectacular accident in the late 1970s, the angular impulse caused by the destruction of a spinning epoxy-glass composite rotor tore a spin pit from its attachment bolts and twisted it around in place, tearing away all the service lines including the vacuum pipe. The vacuum pipe failure admitted air to the chamber, allowing the explosive ignition of epoxy dust, failure of the cover bolts, and ejection of rotor fragments into the surrounding test cell area. Because the incident occurred in a concrete test cell, no injuries occurred.

Properly designed spin test chambers include a separate internal burst-containment cylinder that is not attached to the chamber but is free to rotate under the angular impulse of burst fragments. The chamber mounting bolts are therefore subject to forces not exceeding the friction drag of the containment liner as it slides.

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Soft Liner Extrusion

In order to preserve pieces of broken disks for analysis, many spin test chambers are lined with lead blocks or other relatively soft material to cushion the impact of burst fragments. This soft liner (particularly lead) is also helpful in reducing the formation of metal dust as the burst fragments strike the inner surface of the containment cylinder.

The impact of large-area high-energy burst fragments against the soft liner can expand the liner axially, driving the entire volume of cushion liner simultaneously against the base and cover of the vacuum chamber. This exerts a force equal to the dynamic compressive strength of the soft material times its projected area. This force can be several million pounds, enough to fracture the spin pit cover flange bolts.

SPIN TEST SYSTEMS, which are used extensively in the turbomachinery industry for evaluating the centrifugal strength and fatigue life of high-speed rotating components such as turbine disks and centrifugal compressors, allow stress testing of high-speed components in a controlled environment. Therefore, these systems are faster and less expensive to use than testing in the target engine or machine.

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Fig. 2 — This 36” spin test system was used by Test Devices to burst a rotor and demonstrate that the containment structure would satisfactorily support the event (see “Anatomy of an Accident”). However, the system, which included a spin chamber, turbine - atop the pit with two blue hoses entering the side - and vacuum and oil pumps, was later destroyed in an accident.

Oil Deflagration

In a recent incident, a spin chamber cover was blown off as the machine was being vented. This was an inground chamber, without any lid retention dogs. The vent valve was located next to the chamber and manually operated. Fortunately, the operator had his back turned when the deflagration occurred and was protected from flash burns by his clothing. In this incident, an electric oven was installed in the chamber and the test part temperature was well above the ignition point of the oil. A safety interlock system was in use, with a thermocouple in the oven connected to prevent chamber venting when the oven was hot. Apparently the oil leaking from the spindle seal flowed directly over this thermocouple, cooling it and defeating the interlock. The oil stream impinging on the heated test article could be expected to evaporate rapidly, creating a highly flammable condensate fog.

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Known Versus Unknown Hazards

The accidents described herein illustrate the hazards of operation thus far identified. It is important to remember that there are failure mechanisms that have not yet been observed or reported. Some known hazards involving kinetic energy include burst fragment translational energy, test article angular momentum, cushion liner extrusion, drive turbine burst energy, and drive spindle ejection. Hazards involving chemical energy include oil and metal dust deflagration.

Escape of burst fragments from a spin test chamber is the most obvious hazard of operation. Because the translational kinetic energy of burst fragments is very high, the test chamber must be constructed of high-strength material with sufficient thickness to prevent penetration. An extensive experimental program involving the bursting of disks inside steel containment cylinders was conducted by Westinghouse Research Laboratories in Pittsburgh and presented by Hagg and Sankey at the 1973 ASME Winter Annual Meeting in Detroit1.

Hagg and Sankey's work demonstrated that burst containment is a two-stage process involving first the localized shear strain of material at the perimeter of an impacting rotor fragment and progressing to generalized tensile strain of the entire containment cylinder. The cylinder will survive the burst event if the strain energies in both stages are less than the energy transferred to the liner by the collision of the fragments. Only a portion of the total disk energy need be absorbed by the containment structure during a typical collision. The burst fragments continue to rotate at the same angular velocity immediately after the burst as before it, and their rotational energy is not transferred to the liner, but is dissipated by friction against its inner surface.

High-energy spinning rotors exhibit high values of angular momentum. When these rotors burst, the angular momentum is transferred to the containment structure over a period of milliseconds. The resulting angular impulse can be millions of ft-lbs of torque, impossible to resist with ordinary floor-bolting methods. If the containment cylinder were rigidly attached to the test chamber, it can be predicted that the burst of a heavy rotor would tear the chamber from its mounting bolts.

Properly designed spin test facilities use a containment cylinder that is not attached to the vacuum chamber, but rather is free to rotate when impacted by fragments of the burst disk. Test Devices by Schenck, a company that specializes in the design and manufacture of spin test systems and the testing of rotating machinery, has validated this design by bursting a 600-pound 30-inch-diameter disk at about 14,000 rpm in a containment liner weighing about 12,000 pounds. The liner rotated while the chamber remained firmly attached to the test cell floor. No degradation of the floor bolts or the surrounding concrete floor was observed.

The lead bricks typically used as an inner liner can transfer very large forces to the chamber cover when impacted by rotor burst fragments. The impact force is significantly larger than typical cover flange bolt strength and can easily blow the cover off the chamber.

To prevent the impact of these bricks against the cover with subsequent cover ejection, it is necessary to add a steel brick retention ledge to the inside of the containment cylinder at both ends. This ledge must have sufficient strength to withstand a uniform axial compressive stress of 3000 psi, the maximum observed compressive strength of lead and its normal alloys. Obviously, if a material with higher compressive strength were to be used as a cushion liner, the ledge strength would have to be higher.

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The drive turbine mounted on top of the spin chamber includes a high-energy spinning disk as its primary component. If this disk were to burst at maximum turbine speed, the potential exists for the escape of rotor fragments or ejection of secondary fragments. No such incident, however, has been reported to date.

Drive turbine burst is a hazard that has not been well defined. To evaluate the significance of this hazard it would be necessary to arrange for the intentional overspeed of a typical drive and to establish that burst fragments are contained by the turbine housing.

The inherent limiting speed of an air turbine at 90-psig inlet air pressure produces disk stresses well below material yield. Hence a burst could occur only if there were a flaw in the disk at original manufacture or if a crack were to develop as a result of fatigue or corrosion.

Some operators, however, use high pressure air to increase output torque and shorten cycle time. When a test rotor failure causes a loss of load by shearing the drive shaft, it is possible to accelerate the turbine to its burst speed when using high inlet pressure.

Because the drive spindle is directly connected to the test rotor, a burst event can exert a large vertical force on it, ejecting it from the turbine at high velocity. Because the forces at burst are transverse to spindle axis, such an event is rare. In the only case where it is known to have happened, the cover of the turbine was not in place, so that the spindle was entirely unrestrained from vertical movement.

Fig. 3 — The spin pit cover with stripped retaining bolts is lying on the floor next to the spin chamber after the accident. The explosion destroyed the chamber and made holes in the wall and roof of the building where the experiment was being conducted.

The turbine drive spindle of a modern air turbine is lubricated with oil supplied by an external pump. A spindle seal, either carbon face type or elastomer lip style, keeps the oil from flowing into the spin chamber. In normal operation a small amount of oil passes by the seal into the chamber. When the seal is damaged by careless installation of the drive spindle, the flow can be significant. Spin test systems in industrial use often have a great deal of oil puddled in the bottom of the chamber. The oil leaking from the spindle can be atomized by the high-speed rotating test article, and the residual oil can be atomized by the rotor fragments during burst. If there is a loss of vacuum, a highly flammable oil and air fog can form. The mixture will explode if ignited by friction of the burst fragments against the liner or by contact with a test oven. The deflagration can produce very high internal pressure in the chamber, sufficient to blow off the lid or cover if retention dogs or flange bolts are inadequate.

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Oil deflagration in spin chambers is probably the most common accident in the testing process, but the incidents, with few exceptions, have been mild. It is likely that the relatively low explosion pressures observed are the result of the typically slow venting rates of the chamber. If the oil mist is ignited before the absolute pressure in the chamber reaches atmospheric, the resulting peak pressure will be directly reduced by the ratio of pressure at ignition to atmospheric pressure.

It has been suggested that the oil deflagration problem could be solved by replacing the normal petroleum lubricant used for the drive turbine with a phosphate-ester fire-safe lubricant. A series of tests performed as part of a safety review for the Pantex facility at Sandia National Laboratories in Amarillo, TX, showed that use of such lubricants does not reduce the oil mist deflagration hazard. When the phosphate-ester fluid was atomized in a test chamber and ignited, it produced a peak pressure equivalent to the petroleum oil.

It is very important to note that the oil deflagration event is substantially more energetic than has been previously assumed. The peak pressures measured in experiments at Test Devices' facilities are about twice the values reported in accepted published data. The published explosion pressures were measured in a small-volume cylindrical test vessel, which apparently quenches the deflagration before peak pressure occurs. The tests recently conducted were in a large spherical vessel whose volume was roughly equivalent to that of a typical small spin chamber. Peak pressures measured were about twice those reported in the literature.

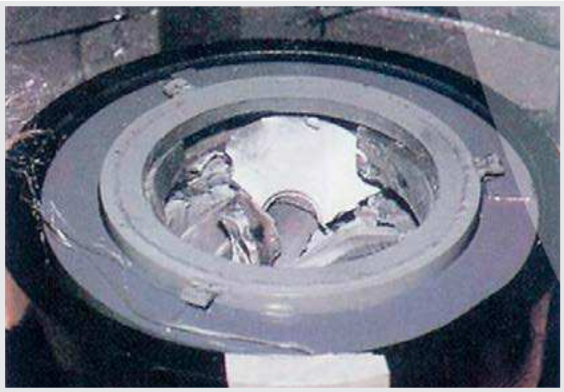

Fig. 3 — To solve the problem, a ledge that would cause the lead to fold back harmlessly into the pit was designed. The model spin pit inside a larger test pit is shown immediately following a lead extrusion containment burst. All the lead was contained inside the pit after the test.

Reactive metals like aluminum, magnesium, and titanium have been used for many years as incendiary devices, flares, and rocket fuel because their oxidation reactions are highly exothermic. Metal dust explosions are an important potential hazard in the spin test process. When a reactive metal rotor bursts, a considerable amount of dust and flake metal can be created as the fragments impact the harder metal of the containment cylinder (particularly if there is no lead inner liner). Because the test is normally conducted under vacuum, the large free surface area of the flakes and dust is available for rapid oxidation. The friction generated between the fragments and the liner provides a ready ignition source.

All that is missing is the oxidizer. Admission of air to the chamber, as the result of burst damage to sight ports or drive spindle ejection is all that is necessary to complete the chain of events ending in an explosion.

Experiments by the U.S. Bureau of Mines on metal dust deflagration were conducted with the same apparatus and procedures used to measure oil deflagration pressures, and therefore the published data on peak pressures must be assumed to be half the actual. Until reliable data are generated, it should be assumed that the worst-case metal dust deflagration will produce a peak pressure of 180 psi.

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Some Recommendations

Issues regarding spin pit safety are serious, and spin pit design should be conducted only by specialists in the field. In general, the following rules are recommended for safe spin testing.

1. Have a safety audit performed on existing spin test facilities, especially if you plan to spin new parts with higher energies or that are made of new materials. Primary issues are retention of the lid, the strength of the cover, and the ability of the liner and vessel to contain a burst.
2. Enclose spin pits in a test cell (usually with concrete walls) and do not allow anyone inside the cell when tests are being run. Test cells are important because all the potential causes of accidents during spin testing are not known.
3. Fill sight glasses with appropriate steel plugs. These glasses allow shrapnel to escape out of the spin pit and oxygen to enter easily.
4. Vent the vacuum pump exhaust line outside the building and use an oil mist coalescing filter to eliminate the discharge of excessive amounts of oil into the air.
5. Install a reliable and safe lid elevator to prevent damage to hands and fingers while operating the spin pit.
6. Spin testing can be reliable, safe, and productive if enough attention is paid to safety issues and the facility is designed to protect the users.

References

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