

## SUPERFLYWHEEL ENERGY STORAGE SYSTEM

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Until recently, the use of flywheel storage systems has been limited to a very few applications. The principal disadvantages of these devices have been the limited energy storage capability (about one-tenth of that of a lead-acid battery), the poor energy storage efficiency (short run-down time), and the danger of catastrophic failure.

Modern technology has provided a tenfold improvement in flywheel energy storage capability since 1900. There have also been significant improvements in rotor drag from bearings, seals, and aerodynamic resistance, resulting in greatly improved energy storage efficiency.

Unfortunately, however, the hazard of catastrophic failure of the conventional steel flywheel has increased, because of the great increase in the energy of the failed pieces in the high-performance steel flywheel. Thus, even these higher performance flywheels have been limited to applications where either adequate failure protection can be provided or (usually) where the performance can be derated sufficiently to provide an adequate margin of safety.

This margin typically increases as the flywheel size increases. For example, the theoretical maximum performance of an optimized steel flywheel using the best available material is about 26 watt-hours per pound. Practical limitations reduce this to about 12 watt-hours per pound for a small, 30-pound flywheel (ref. 1). In a current program involving a 1400-pound steel flywheel, the rated performance is 6 watt-hours per pound (ref. 2), while a third steel flywheel weighing 480,000 pounds is rated at 0.75 watt-hours per pound (ref. 3).

For the past 3 years the Applied Physics Laboratory has been studying a new superflywheel concept. It appears to offer greatly improved safety, and its performance can be better than that of the best optimized steel flywheel. Its configuration allows sufficient distribution of failed particles in size, direction, and total time; thus, effective failure containment appears to be a practical objective.

The use of superflywheel energy storage will considerably enhance the performance of future onsite energy systems, such as solar and wind energy systems. Its chief advantages will be lower total cost and freedom of maintenance of the storage system. It will have several times the operating life of lead-acid batteries, and it will also readily accept

high-power peaks associated with heating and air conditioning equipment and cooking. This same capability to accommodate high power peak loads makes the flywheel especially attractive for wind power machines, where peak power can easily range up to several times average minimum power.

The amount of kinetic energy that can be stored in a rotating flywheel is equal to the specific strength of the material used times some constant related to the geometry of the flywheel. The basic element of the superflywheel is the thin rod shown in figure 1. A number of these rods are assembled in a pregrooved hub lamina (fig. 2) so that they fan out in radial orientation (fig. 3). Thus, the free ends of all of the rods are in essentially pure tension when the assembly is rotated. Adjacent layers of hub laminae are assembled  $90^\circ$  in rotation to each other so as to form the circular brush configuration (fig. 4).

The failure of any rod represents but a tiny amount of the total energy in the rotor, and even if all of the rods failed simultaneously, the failed pieces would be distributed evenly around the periphery; thus, the stress concentrations are minimized in the containment structure from the failed pieces.

In contrast, the stress concentrations in the containment structure caused by the failure of a conventional solid steel flywheel could be several thousand times as great, since it would (typically) break into three large pieces, instead of thousands of tiny pieces.

Another advantage of the superflywheel configuration is that it allows optimal use of filamentary composite materials. These materials not only exhibit many times more strength to density (hence energy storage capability) than steel, but they absorb very large amounts of energy upon failure, as illustrated in figures 5 to 10. A number of 30-inch long rods about 1 pound each (fig. 5) were spun to destruction in a special test setup (fig. 6). In each test a steel ring was used to contain the fragments at failure. From the destruct sequence shown in figures 7 and 8, it can be seen that the rod is completely destroyed before the steel ring has begun to move from the impact of the failed pieces. The rod virtually exploded into the dust-sized particles shown in figure 9. Also, by comparing the shape of the steel ring after the test (fig. 10) with its other known characteristics, it was established that only about  $1\frac{1}{2}$  percent of the kinetic energy in the spinning rod reached the steel ring as impact energy. It would thus appear that the superflywheel brush configuration offers the first prospect of realistic failure containment for a high performance flywheel.

There now appear to be about ten different materials that seem to offer more economical energy storage (W-hr/\$) than the lead-acid battery. Some of these materials are glass, fiber glass, Dupont Fiber B and PRD-49, music wire, and some new proprietary materials. Thus, a successful superflywheel development would provide an energy storage system with the economy of the lead-acid battery, but without any of its limitations (maintenance, depth of discharge, low power peak capability cycles to failure, emissions, low efficiency, dc to ac conversion, etc.).

Also, a wind power system using the superflywheel for energy storage can be considerably more efficient than systems using any other known energy storage concept. This stems mainly from the fact that the wind machine energy can be transmitted directly to the flywheel through gears and shafting at very high efficiency. The flywheel, in turn, can be connected directly to the ac generator without the need for gearing. A nominal flywheel speed range of 2:1 can be accommodated by several generator types capable of producing constant voltage and frequency output under these conditions.

#### REFERENCES

1. Lawson, L. J.: Design and Testing of High Energy Density Flywheels for Application to Flywheel/Heat Engine Hybrid Vehicle Drives. SAE Paper No. 719150, 1971.
2. Superflywheel Meeting at Airesearch, Division of Garrett Corporation, Los Angeles, Nov. 2, 1971.
3. Superflywheel Meeting, Inductive Energy Storage Task Group, Naval Research Laboratory, Mar. 13, 1972.

#### DISCUSSION

Q: Have you found PRD-49 is better than carbon for your purposes?

A: The one thing I failed to point out is that the most critical thing is energy storage per dollar, watt hours per dollar. Never mind amperes per cubic foot or square foot or watt hours per pound or anything else, except of course safety, which is on top of the list. PRD-49, at the present time, is about one-tenth the cost of graphite fibers and also has about the same performance. Therefore, it's ten times as good, if all other things are equal, and with PRD-49 they essentially are. It just so happens there is one material which is almost a hundred times better than PRD-49. And that happens to be wood. The strength of wood is about one-tenth the strength of steel; the density of wood is about one-tenth the density of steel. So the strength and density are the same. The energy density is the same as steel; in fact, it's a little bit better - 20¢ per pound.

Q: I understand that you use this material because of the tension. The problem seems to be two-fold as I understand it. The problem is the angle of the wire. This angle is not safe. Is that the reason why you choose the brush type?

A: Are you talking about the Gyroscopic forces?

Q: If you wound the wire, then when the angle comes up a problem arises. The energy density is high for a wound wheel.

A: That sounds like it's true, but it's not. You get more theoretical energy per space. No one in the published literature has ever achieved more than about 30 percent of the theoretical energy in a wound configuration. The reason is very simple. The only place on that wound wheel where the stress lines up with the filament is the

outer edge. Everywhere else there is a radial component, which is unfortunately a differential radial component with radius and therefore will always break in concentric rings. The only way you can stop this is to add radial filaments. It does turn out that there are combinations of orthogonal filament arrangements we have patents on which can be used to make a solid wheel. It is applicable for some materials like fiberglass, Scotch ply, and so on. In my opinion, the reasons for doing this are economics versus safety. If you're building a million pound wheel, you would never build it this way. This configuration I'm talking about in a million pound wheel would have no component in it except the hub that I couldn't carry over my shoulder in one arm.

Q: It is interesting that about 17 years ago I happened to be with the General Electric Company in the space power work. When we looked at flywheels then and with the high strength steels that we had, without the benefit of these composite fibers and fiber technologies, I just looked at the prediction we made then; it was 26.4 watt-hours per pound.

A: It's about 26 watt-hours per pound maximum now. The Germans are building a 480,000 pound flywheel, and it's rated at three-quarters of a watt-hour per pound.

Q: When we speak of the energy inherent in the rotation of a mass like the flywheel, we very customarily calculate that energy on the basis of how much is stored on the basis of full rotational speed minus the zero energy at standstill. Immediately then, there are two questions. The first of these is we must recognize that this energy is in a mechanical and not electrical form. In the second place, just as we can't expect storage batteries to provide us with the full output, in other words, drain them to zero level of content, we at the same time can't effectively expect all that energy from the flywheel. So I would like to ask you to address a few comments to the dual points.

One is how and with what effectiveness, with what degradation if you will, do we extract this energy on a repetitive in and out basis. And secondly, how can some sort of a fairly steady-state extraction of that energy take place, say from the standpoint of non-fluctuation of the voltage, rpm frequency, or whatever you intend to do with it. Could you give us a few comments on these?

A: How much energy is left in the wheel is of no consequence since in this instance that part of the energy never gets taken out. Even if it were, if I operated only over a speed range of 4 to 1, I can take 96 or 99 percent of the energy out of the wheel. On the question of mechanical energy versus electrical energy, we do not start with electrical energy. We start with mechanical energy; all I need is a contiguous generator of a variable field pole type, for example, which can accept the 2 to 3 to 1 input speed range and hold the output frequency precise and the output voltage within the required tolerances of approximately the percent. Now, if I go directly from the wind machine to the flywheel, the transmission energy is 100 percent.

It is not efficiency that I lose, it is a function of how long it takes the flywheel to spin down. In a rotor the size that would be adequate for a home installation, Professor Beams at the University of Virginia had a magnetically suspended rotor (several hundred pounds) adequate for a home installation with which he measured the deceleration rate of about 1 percent per week in his vacuum container. Now, somewhere between what he is doing and what is real, live practicality, we believe there is a realizable goal. We see a number of programs being initiated for the combination magnetic and mechanical bearings which can achieve a large measure of that efficiency. Now, to answer your final question, I've gone through many calculations and I can't get much below 80-percent efficiency from energy in to energy on the line as opposed to the 30's, 40's, and 50's that you'll get with every other system. It's that way. There isn't anything else in the system, whether you use the generator at 90-percent efficiency, and the electric motor to drive it, or if you connect it directly.

Q: I think I missed one very important point here. We are dealing with very high rotational speed disks and very slow speed windmills. How do you envision this coupling? You are not going to drive one of these disks directly with a windmill without a fantastic gear. How do you get this flywheel running at the enormous speed necessary?

A: There are two ways you can get the flywheel speed up. In the smaller systems, in which the size of the flywheel would be (could be) small compared to the rpm that you want to operate the wind machine in, you would have to change the speed mechanically by some means: timing belt, or gears, or rollers, all three are applicable. In the larger machines, it's much easier just to make the flywheel diameter compatible with the speed you want.

Q: How do you get this speed differential? You are operating a windmill at, say, 30 rpm.

A: Well, if you are operating a windmill at 30 rpm you can gear it up using pulleys, gears, rollers, and the like.

Q: You need a continuously variable speed transmission in order to accomplish this.

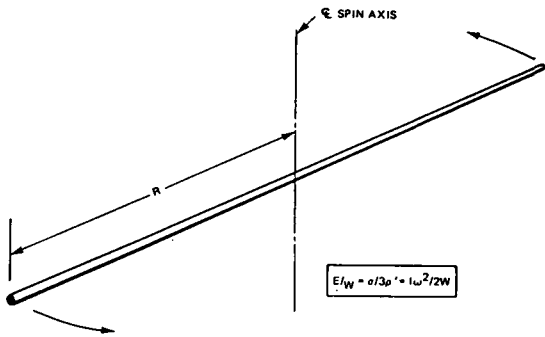
A: You either need a continuously variable speed transmission or you need something like a variable speed pole generator.

Q: How do you charge mechanically the flywheel? How do you charge at the various speeds? How do you build up the speed of the flywheel unless you have mechanical transmission to accomplish that?

A: I'm saying you can do it either mechanically or electrically. It's the reverse of driving an automobile, if you will. As a matter of fact, it's exactly like driving an automobile downbrake with regenerative brakes on. It's being done all over the world. And you can, indeed, either mechanically vary a transmission, which I had in my efficiency calculations (I had an electric variable field pole generator), or you could use a variable field pole motor.

Q: You have a windmill converting wind to electricity?

A: Definitely. Oh, yes. I'm sorry, I didn't mean to leave that out.



- E = KINETIC ENERGY OF ROTATING ELEMENT (IN-LB)
- W = WEIGHT OF ROTATING ELEMENT (EXCLUSIVE OF SHAFT AND HUB) (LB)
- $E/W$  = SPECIFIC ENERGY (IN-LB/LB)  
(MULTIPLY BY  $0.314 \times 10^{-6}$  TO CONVERT TO W-H/LB)
- $\omega$  = ROTATIONAL SPEED (RAD/S)
- $\sigma$  = STRESS AT ROTATIONAL SPEED  $\omega$  (PSI)
- $\rho$  = MATERIAL WEIGHT DENSITY (LB/IN<sup>3</sup>)
- I = MOMENT OF INERTIA ABOUT SPIN AXIS (IN/LB/S<sup>2</sup>)  
(FOR THIN ROD,  $I = R^2W/3\rho$ )
- g = GRAVITATIONAL CONSTANT = 386 IN/S<sup>2</sup>

Fig. 1 ENERGY STORAGE CAPABILITY OF THE STRAIGHT FILAMENT

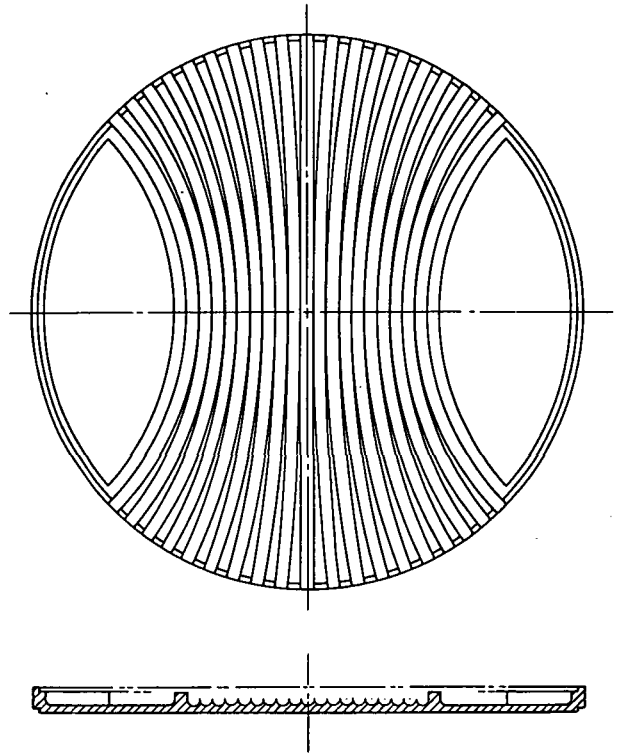


Fig. 2 TYPICAL HUB LAMINA

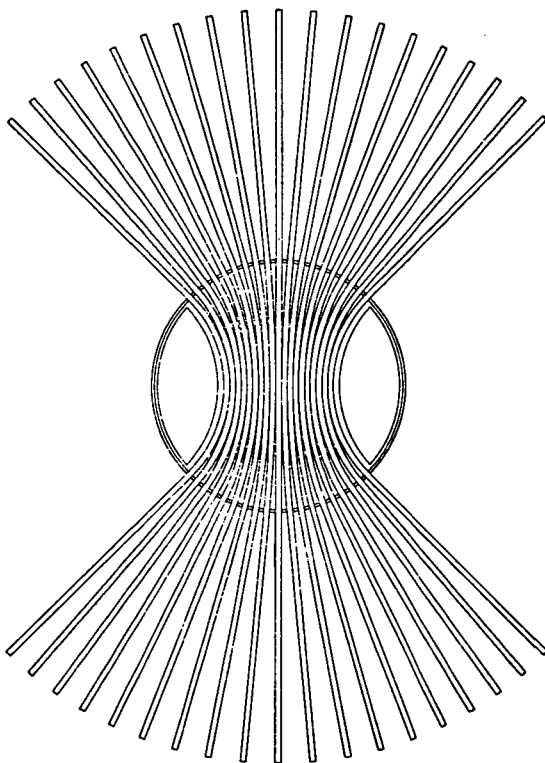


Fig. 3 HUB LAMINA WITH RODS

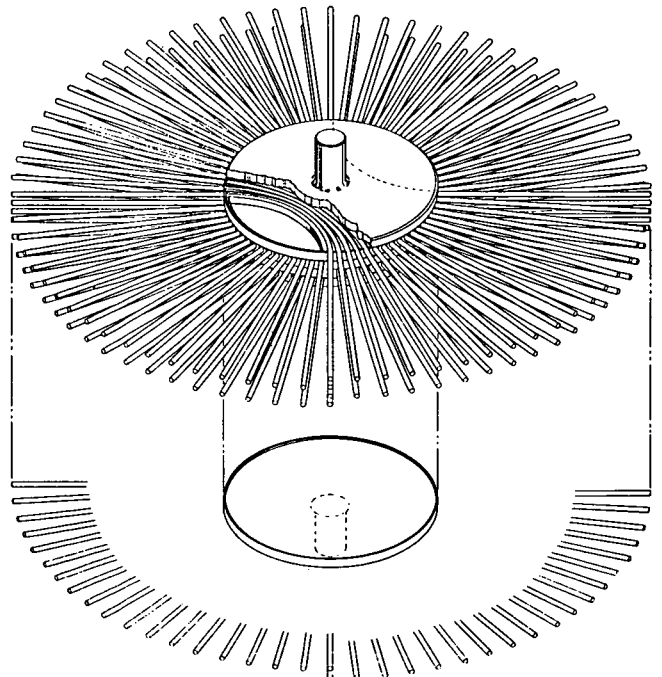


Fig. 4 FANNED CIRCULAR BRUSH CONFIGURATION

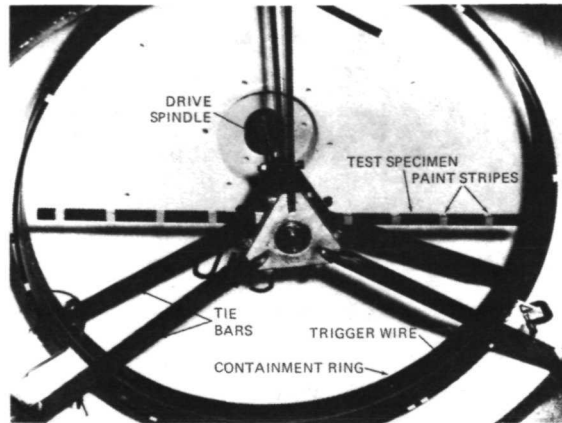
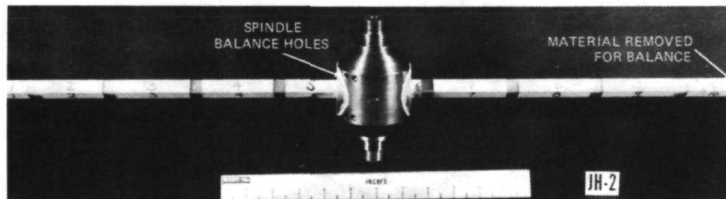
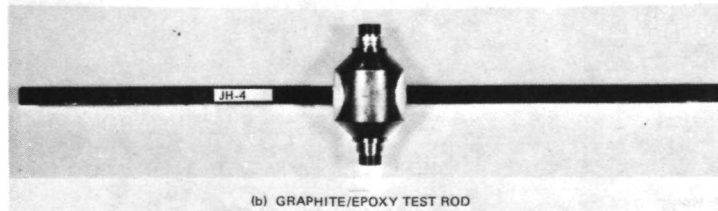


Fig. 5a INSIDE VIEW OF SPIN CHAMBER



(a) S-GLASS/EPOXY ROD POTTED INTO HUB



(b) GRAPHITE/EPOXY TEST ROD

Fig. 5b TYPICAL SPECIMENS FOR NAPTC TESTS

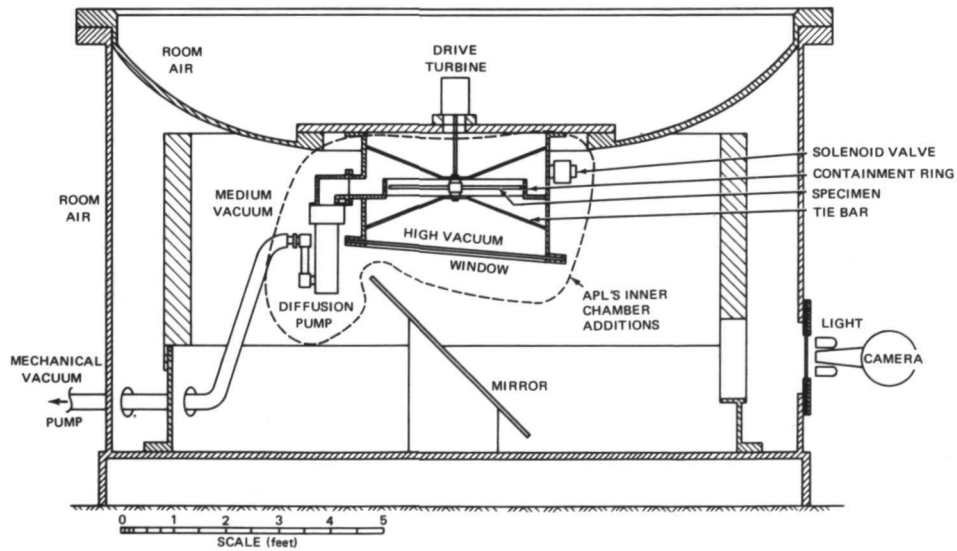


Fig. 6 GENERAL ARRANGEMENT FOR 1-POUND ROD TESTS AT NAPTC, PHILADELPHIA

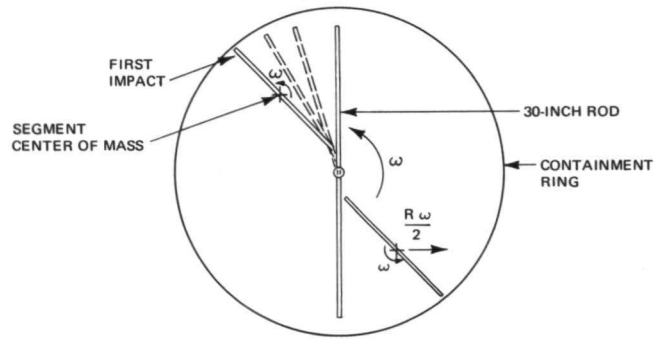


Fig. 7a KINEMATICS OF ROD FAILURE (ASSUMING TWO EQUAL SEGMENTS)

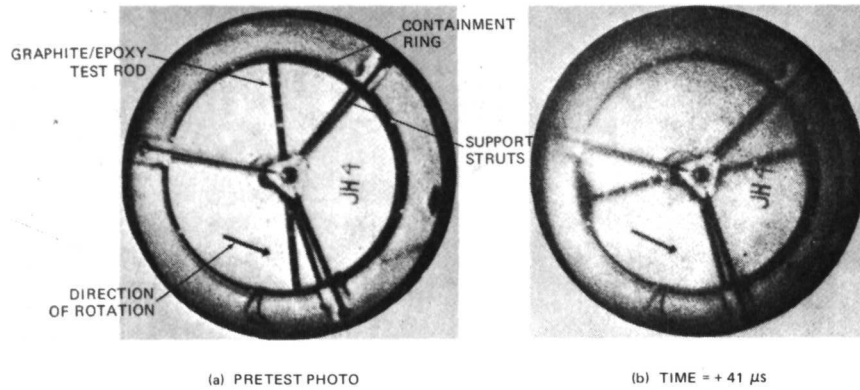


Fig. 7b PHOTOGRAPHS TAKEN BEFORE RUN JH-4 AND 7 TIMES AFTER FAILURE TRIPPED PHOTOGRAPHIC SYSTEM

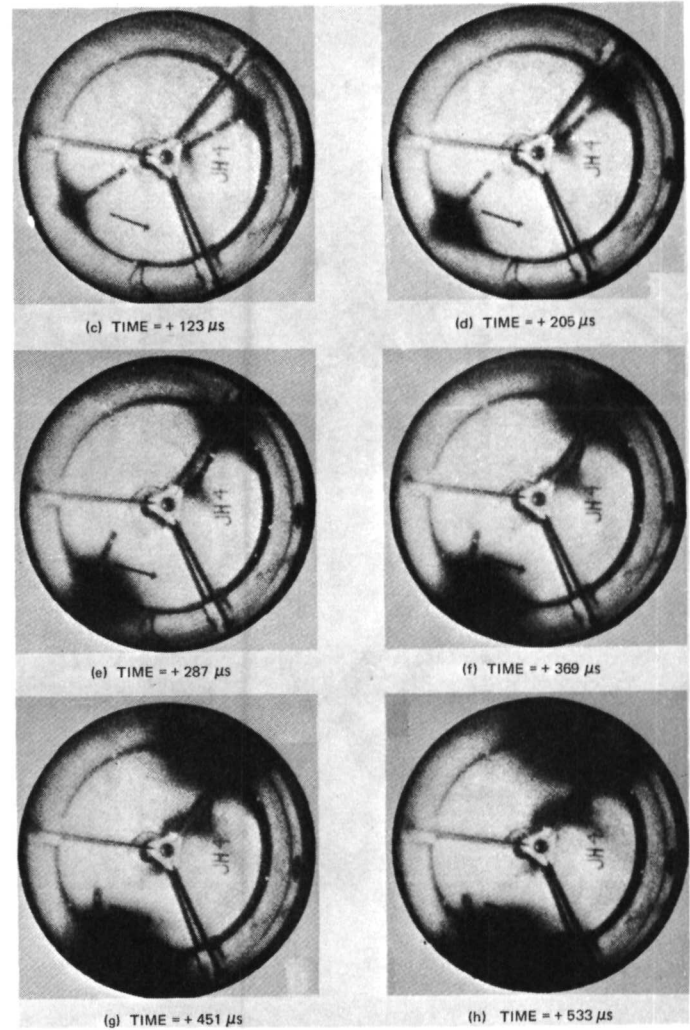


Fig. 8 PHOTOGRAPHS TAKEN BEFORE RUN JH-4 AND 7 TIMES AFTER FAILURE TRIPPED PHOTOGRAPHIC SYSTEM



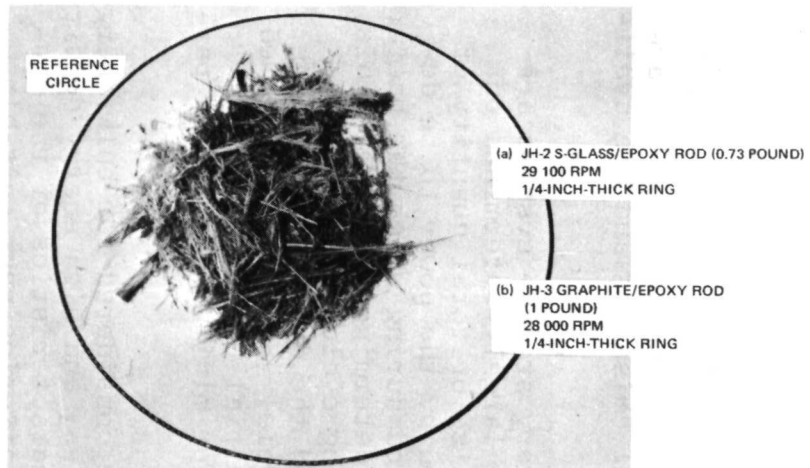


Fig. 9a S-GLASS/EPOXY FRAGMENTS FROM TEST JH-1

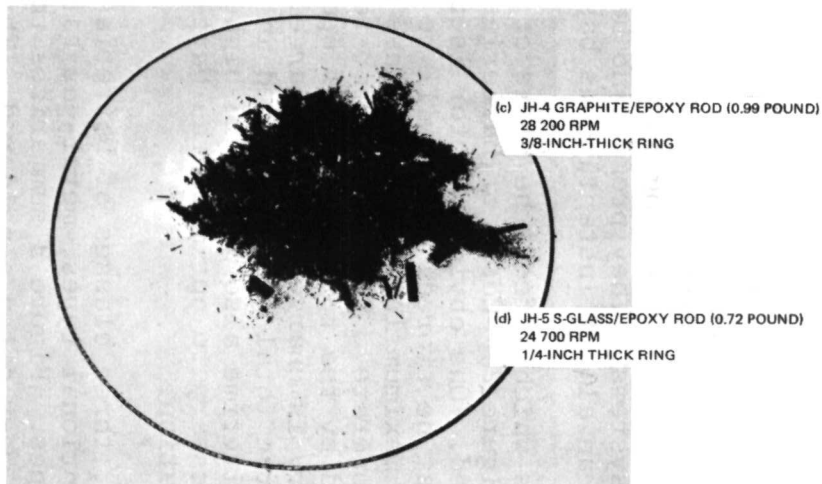


Fig. 9b GRAPHITE/EPOXY FRAGMENTS FROM TEST JH-3

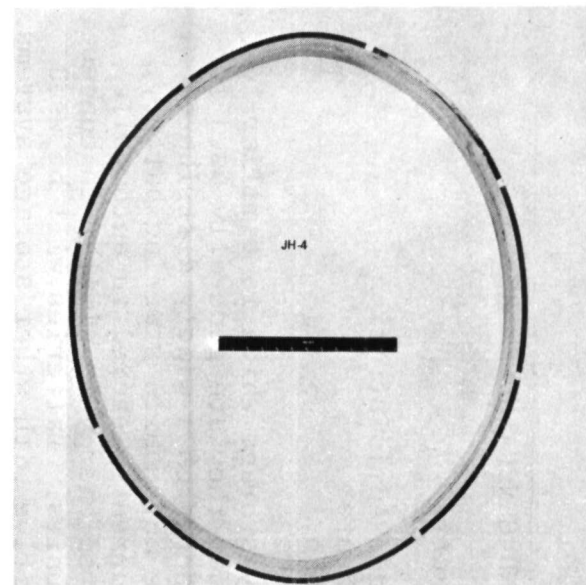


Fig. 10a DEFORMATION ON OF 3/8-INCH-THICK STEEL RING; ROD ENERGY OF 820 000 IN-LB

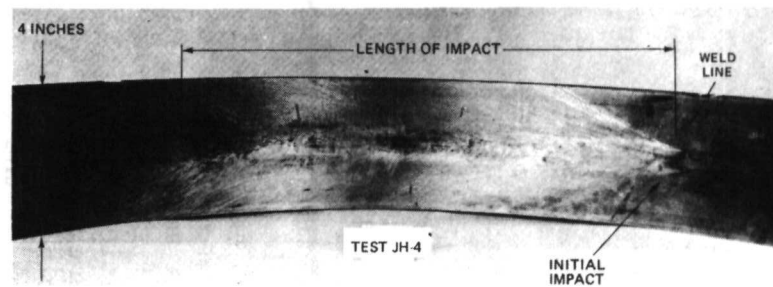


Fig. 10b ONE OF THE IMPACT ARCS ON THE CONTAINMENT RING