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A UNIDIRECTIONAL ROTARY SOLENOID AS APPLIED TO STRONGLINKS

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ABSTRACT

This paper describes the design goals and results of an advanced development stronglink project with special emphasis on a new rotary solenoid concept.

INTRODUCTION

During the handling, storage, transporting, and deployment of weapons, it is inevitable that accidents will occur. With nuclear weapons, it is mandatory that such accidents not result in nuclear detonation. Stronglinks are one of several interlocks on each weapon, designed to prevent accidental detonation in the event of abnormal environments (impact, fire, crush, etc.).

Stronglinks are electromechanical devices that prevent energy from being applied through a "barrier" to certain components in an "exclusion" region unless there is human intent that such energy be applied. The stronglink is an energy gating (or switching) mechanism with a built in "combination lock". The only combination that will open this lock is an electrical unique signal (UQS) which allows the device to be driven from a "safed" state to an "enabled" state. Stronglinks are used strictly for safety purposes as differentiated from other devices used for security reasons.

The term "stronglink" comes from a concept of juxtapositioning this device with an environmentally "weak" device ("weaklink"). The weaklink is a component vital to the arming of the weapon (example: capacitors). Usually an attempt is made to "sandwich" the stronglink inside the weaklink so that any environmental "attack" on the stronglink will first irrevocably disable the weaklink before damaging the stronglink.

Stronglinks in the field are generally "one-shot", single try devices. Each weapon system contains two stronglinks of different designs that respond to different UQS electrical pulse patterns. This is to prevent the possibility of a common mode of failure in the event of some unforseen weakness in one device.

Stronglinks consist of three major components:

1. Energy gating mechanism
2. Discriminator mechanism (combination lock)
3. Drive mechanism (usually two rotary solenoids)

Figure 1 shows the advanced development stronglink assembly with the major components indicated.

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GOALS

The primary goals of this advanced development project were to achieve a smaller package (especially in the direction parallel to the solenoid axes) and to provide safety enhancement. Secondary goals were simplicity, reduced enabling time, and a more energy efficient device.

UNIQUE SIGNAL (UQS)

The unique signal is the only electrical pulse pattern that will allow the stronglink to advance to the enabled condition (see Figure 2). The UQS is a pre-determined pattern of groups of "A" and "B" events. Generally there is a mixture of twelve "A" events and twelve "B" events for a total of twenty four events.

The twenty four events give a gross total of 2^{24} possible combinations (16,777,216). The grouping of "A" and "B" events for a UQS format is rigorously analyzed to provide the highest possible odds against the signal being randomly generated in an abnormal environment. Grouping of events in a repetitive ~~nature~~ or "symmetrical" format is not allowed.

The "A" pulse event must clearly differ from the "B" pulse event with some characteristic such as amplitude, duration, polarity, point of application, etc. In one production stronglink, the two events are "short" (100 ms) and "long" (400 ms) pulses applied through a single circuit to a single solenoid. The solenoid releases a clock which in turn "shifts gears", depending on how long power is applied to the solenoid. In all other designs, two independent solenoids are used (with no clock). The solenoids are pulsed through two independent electrical circuits. It is the interplay of the two solenoids and the discriminator mechanism that either allows the stronglink to advance to the enabled condition, or irreversibly lock in a safe condition.

ENERGY GATING MECHANISM

Several different types of devices (with their related locking mechanisms) have been considered to control the passage of energy through the barrier into the exclusion region. Work continues on new concepts with the goal of further nuclear safety enhancement. The devices include locks on alternator shafts, gas valves, switch contact rotors, light shutters, magnetic flux shutters, and a device that moves a small portion of the physics package.

Current production stronglinks use switch contacts, magnetic flux shutters, and the physics package mechanism to perform the energy transfer function. This advanced development stronglink uses the magnetic flux shutter mechanism for energy gating.

With the magnetic flux device, an electrical transformer is split into its primary and secondary halves with an air gap between the primary and secondary C-cores. A disk ("safe/enable wheel") is placed in this air gap (see Figure 3). The disk, except for localized magnetic "windows", blocks the passage of magnetic flux lines between the primary and secondary for all areas of the disk, except the windows. The discriminator mechanism locks the disk in the flux blocking mode unless the stronglink receives the UQS electrical pulse pattern. On receipt of the UQS, the disk is rotated from the "safe" position to the "enabled" position, allowing the primary to energize the secondary through the magnetic windows.

The primary lies outside the exclusion region; the secondary lies inside. The advantage of this type of energy transfer device is that wires are not required to cross the barrier into the exclusion region. This eliminates a path for electrical energy to cross the barrier (from lightning or any other source).

The disks are fabricated from a laminated material with ferrite windows. The laminates used to date are copper-steel-copper. Some work is also being done with a silver-nickel-silver laminate. The ferrite material is a solid solution of iron oxide and manganese oxide. The ferrite window is surrounded by a copper ring which provides magnetic isolation from the rest of the disk.

Physically the ferrite material is similar to a ceramic, which has created a fair amount of manufacturing problems. The windows are in the shape of a pair of half moons. The half moons are fabricated from a solid disk with a slitting (grinding) operation. Yields are not really satisfactory due to cracking of the ferrites. The ferrites also require a metalizing operation so they can be soldered into the copper rings.

Due to these processing problems, there have been continuing studies of alternate processes and alternate materials. An alternate design being considered uses an iron-nickel ribbon laminate construction similar to the transformer core construction. The laminates must stand on edge parallel to the disk axis of rotation to allow flux passage through the wheel.

Discriminator Mechanism
("Combination Lock")

The discriminator mechanism is a type of mechanical "maze" representing the predetermined electrical UQS pulse pattern. If the solenoids receive the UQS, each pulse allows a correct step through the maze. An incorrect pulse pattern leads up a "blind alley" in the maze, causing stronglink lockup.

With the exception of the above mentioned stronglink containing the single solenoid and clock, all of our stronglinks are used in the field as one-shot, single try devices. Lockup is electrically irreversible, and if it occurs, manual access is required to reset the device. The noted exception is a multiple try device that is electrically resettable with an extra long (1200 ms) reset pulse. This device requires a much longer UQS (more events) to compensate for the multiple try feature. For test purposes, all units are electrically resettable when correctly enabled with the UQS.

Past stronglinks have contained one of two general types of discriminator mechanisms. The first type features a gate (or two gates) working in conjunction with a discriminator wheel containing two rows of some type of teeth about the periphery of the wheel. One of the rows contains groups of teeth representing UQS "A" events; the other, "B" events. Where there is a group of teeth in one row, there are corresponding voids in the other row. When the "A" event gate is closed, the "B" event gate is opened and vice versa. The enabling logic thus requires the gate to be open for the row with advancing teeth, while the other gate is closed in the area of the voids. After a group of teeth in one row has passed through its gate, the gates must change states to allow for passage of teeth in the other row. If a tooth advances into a closed gate, it is blocked, and the gate can no longer be opened. Lockup has occurred.

The second type of discriminator mechanism uses a type of pawl/ratchet wheel mechanism for signal discrimination. The ratchet wheel(s) contains "shallow" drive teeth and "deep" penalty teeth in groups representing the UQS. The enabling logic requires the pawl to drive the ratchet wheel only on the shallow teeth and to "skip" over the deeper penalty teeth. With an incorrect signal, the pawl becomes "entrapped" in a deep tooth, blocking the discriminator wheel from further advancement, and again requiring manual access to reset the device.

The subject stronglink features a new type of discriminator mechanism called a "spur gear discriminator" (see Figures 4 and 5). The mechanism consists of two spur gear assemblies, one representing the UQS "A" events; the other representing the UQS "B" events. Each assembly has sixteen tooth positions and advances one tooth position per UQS event. Each assembly consists of four levels of gear segments, with groups of teeth representing the UQS. One solenoid drives the "A" assembly; the other drives the "B" assembly.

In a "normal" pair of mating external spur gears, one gear rotates clockwise; the other counterclockwise. In this device, both gear assemblies rotate in the same direction (shown counterclockwise). Thus, at the interface "mesh", teeth of one assembly are advancing toward teeth of the other assembly. Each gear assembly will always have at least one tooth at one level in the mesh position for each of the sixteen positions. Each gear assembly has a hold pawl (not shown) in its drive mechanism that prevents the assembly from backing up, i.e., each assembly can only rotate in the direction shown.

If the condition occurs where an "A" assembly tooth and a "B" assembly tooth of the same level are in the mesh position at the same time, the mechanism is locked. Neither assembly is able to advance or back up, which would be the response to an incorrect electrical pulse pattern. The enabling sequence thus requires sequentially pulsing the solenoids in such a manner as to prevent teeth from the two assemblies from ever coming into contact at the mesh position (the UQS pattern).

Consider the first two UQS pulse events (an "A" event followed by a "B" event). Looking at level "W", if in error, we first pulse the "B" assembly, tooth B2 advances to the mesh position opposing tooth A1, and lockup occurs. If the "A" assembly is correctly pulsed first with a single pulse, tooth A1 of level "W" moves out of the mesh position, allowing the passage of tooth B2. If, again in error, the "A" assembly receives two or more pulses instead of the correct single pulse, tooth A3 of level "Y" will advance to the mesh position opposing tooth B1 and lockup has again occurred. The mechanism operates similarly throughout the UQS pulse sequence. If, for any group of "A" or "B" events, the related solenoid receives more or fewer pulses than specified in the UQS, lockup will occur.

Safety is enhanced because this mechanism presents the same level of restraint throughout a pulse cycle (at least one tooth is always in the path of the opposing gear assembly). With existing devices the level of restraint can vary, depending on the exact gate position or the depth of pawl/ratchet wheel engagement.

This device is simpler than the pawl/ratchet mechanism and should have fewer dynamic problems and frictional problems, as the two gear assemblies never come into contact during a normal operation. This device has the further advantage of having half the UQS events on one "wheel" and half on the other as opposed to existing devices having all UQS event positions about the periphery of a single wheel. This allows each wheel diameter to be reduced by half while maintaining the same tooth-to-tooth spacing (tooth size). This in turn reduces the inertia reflected to the solenoid to one-sixteenth of existing values. Since four levels (or rows) are required instead of two, the inertia ends up at one-eighth of existing values.

DRIVE MECHANISM

Oscillatory Rotary Solenoid

Each interrupted transformer type stronglink in production uses two 4-pole cylindrically shaped rotary solenoids (see Figure 6) to receive incoming electrical pulse patterns and drive the discrimination mechanism. Rotary solenoids are used since they are more readily balanced against G forces than linear solenoids. The solenoid rotors operate between two stop pins, impacting one pin when energized; the other when de-energized. The rotor stretches an extension spring or winds a torsion spring during the energized stroke. The spring returns the rotor in the opposite direction when the solenoid is de-energized. This oscillatory motion is converted to a rotary motion by the discriminator pawl-ratchet wheel mechanism. The drive pawl picks up a new ratchet wheel tooth on the energized stroke and advances the ratchet wheel one unique position on the de-energized spring return stroke (representing one UQS event).

Figure 7 shows the oscillatory rotary solenoid magnetic torque output (measured without the return spring) and it shows the return spring torque; both are plotted against rotor displacement. Without stops, the magnetic torque goes from a zero value; to some maximum value; and back to zero over 45 deg. displacement. The first zero torque value occurs when the rotor poles are midway between the stator poles. The second zero torque occurs after 45 deg. rotor displacement when the rotor and stator poles are aligned. The area (12.8×10^{-3} J) under the magnetic torque curve between 0 deg. and 45 deg. represents the gross energy available to operate the mechanism for one on-off pulse cycle. Since the device cannot start with zero torque, the rotor is biased from the initial zero torque position with one of the rotor stop pins. For the device illustrated, the second stop pin limits the rotor travel to 24 deg. within the 45 deg. total displacement shown.

The area (3.46×10^{-3} J) under the spring curve represents the actual energy stored in the spring. As can be seen, the maximum spring torque is determined by the minimum solenoid torque. While some margin is required between the magnetic torque and spring torque, most of the area between the two curves represents wasted energy. More than being wasted, the excess energy aggravates "bounce" conditions during impact between the rotor and its energized position stop pin. With past development units, this sometimes caused "double pulsing" of the ratchet mechanism and required damping of the discriminator ratchet wheel to keep the bounce within acceptable limits.

While there have been some dynamic problems with the oscillatory solenoids, the real driving force for consideration of a new solenoid design related to packaging. The axial length of the solenoid cylindrical housing was too great for a "flatpack" stronglink geometry. Consideration was given to laying the solenoids on their sides and using a right angle drive, but the added complexity was undesirable.

Unidirectional Solenoid

The flatpack application led to consideration of a two-pole, horseshoe shaped stator design, with a two-pole rotor. For approximately the same energy output, this configuration gives a larger package measured normal to the rotor axis, but its axial length is half the cylindrical package length. The overall volume of the horseshoe package is slightly less than the cylindrical package.

After a fair amount of "cogitation" over the two-pole design, the unidirectional solenoid concept occurred. Why not stretch a spring slightly beyond high center ("toggle style") during the energized stroke, and have the spring continue the rotor travel in the same direction during the de-energized stroke?

The two-pole rotor and stator (horseshoe) were originally considered for the unidirectional solenoid concept, but eventually a two-pole horseshoe stator and a four-pole rotor were chosen (see Figure 6). Viewed parallel to the rotor axis, the four-pole rotor profile is identical to the oscillatory solenoid rotor.

Since magnetic flux lines pass through all four poles on the oscillatory device, and only two poles with the unidirectional device, the axial pole thickness of the unidirectional rotor has been doubled. This provides the same area rate of change during rotor and stator engagement for both devices. With the same flux density for both devices, torque-displacement characteristics are nearly the same. Some differences occur, apparently due to different geometry of the flux leakage paths.

The "over high center" spring action is achieved with a four-lobed cam (see Figure 8) attached directly to the rotor, plus a cam follower, and an extension spring that loads the follower against the cam. The rotor-cam rotates 45 deg. during the solenoid energized stroke, and an additional 45 deg. in the same direction during the de-energized stroke, for a total rotor-cam rotation of 90 deg. for each on-off electrical pulse. When energized, the rotor-cam drives the follower "uphill" on the cam (stretching the extension spring) for approximately 35 deg rotor cam rotation, at which time the follower crosses the cam high point (spring "high center"). The follower then goes slightly "downhill" to the 45 deg. end of energized stroke position, where it stays magnetically detented as long as the solenoid is energized. When the solenoid power is turned off, the stored spring energy forces the follower "downhill" on the cam, driving the rotor-cam forward for the 45 deg. de-energized stroke. The rotor cam stays at this position, mechanically detented by the spring loaded follower, until the solenoid is re-energized to repeat the on-off cycle on the next cam lobe. Note: except for flatpack considerations, this unidirectional cam mechnism could be applied to the original cylindrical solenoid, converting it from an oscillatory to a unidirectional device.

Advantages

The unidirectional device has significant advantages over the oscillatory device. Figure 9 compares the packaging of the two types of solenoids and their discriminator mechanisms and indicates the "flatpack" advantage of the unidirectional device.

Since it is no longer necessary to convert oscillatory to rotary motion, a simple direct gear drive can replace the pawl-ratchet wheel mechanism. This eliminates the continual impacting and drag of the ratcheting operation, reducing wear, friction, and dynamic problems.

The unidirectional solenoid, with gear drive, advances the discriminator wheel one unique position on the energized stroke, and a second unique position on the de-energized stroke. The oscillatory solenoid stores spring energy on the energized stroke and advances the discriminator wheel a single position on the de-energized spring return stroke. The unidirectional solenoid can therefore go through an equal number of unique discriminator wheel positions (UQS events) with half the number of on-off solenoid pulses. All else being equal, this allows enabling in half the time, and halves the battery energy requirements. The number of possible UQS "A" and "B" event combinations is unchanged, so the "uniqueness" of the pattern is unaffected.

The unidirectional solenoid cam is contoured to "match" the magnetic torque-displacement curve, so the shape of this curve is immaterial. The only critical feature of the curve is the area (energy) under the curve. With oscillatory devices it is very difficult to match solenoid output torques with spring torques.

The unidirectional solenoid also has advantages compared to a stepper motor. The stepper motor requires sequential energizing of multiple coils to achieve its action (vs the rotary solenoid single coil). For comparable housing volumes, the stepper motor individual coils and magnetic flux paths are necessarily smaller. They thus produce much less torque for a much smaller displacement. The stepper motor requires a more complex programmer to sequentially energize the coils than is required for the simple on-off pulses of the rotary solenoid. Finally, while the bi-directional capabilities of the stepper motor might have advantages for other applications, this capability is not an advantage for our existing discriminator mechanisms. Since the stronglinks are one-shot, single try devices, the ability to "back out" of a locked position cannot be allowed.

Energy

Figure 10 shows the torque-displacement curve for the unidirectional solenoid magnetic output (without a spring), and it shows the torque-displacement curve for the cam-spring mechanism. The lower portion of the figure is an X-Y schematic of one of the four cam lobes, relating follower positions to the various torque conditions. Similar to the oscillatory solenoid, the magnetic torque goes from a zero value, to some maximum value, and back to zero during 45 deg of rotor rotation. The initial zero torque value occurs when the rotor poles are symmetrically positioned about the stator poles; the second occurs when two of the rotor poles are aligned with the two stator poles. The area under the torque-displacement curve from 0 deg to 45 deg represents the total gross energy available to drive the rotor-cam assembly through one on-off 90 deg pulse cycle.

Again, the device is unable to start with zero magnetic torque, so the rotor is biased 7 deg in the direction of desired rotation. With the unidirectional device, the rotor must operate through multiple revolutions, so rotor stop pins are not used. The initial 7 deg bias is attained by the mechanical detenting action of the cam follower at the root position of the cam. The energy represented by the area under the magnetic curve from 0 deg to 7 deg is "lost" for driving purposes, since power is off while the cam follower passes through this portion of the cam.

To achieve 45 deg rotation during the energized stroke starting from the 7 deg biased position requires that the rotor pass through the second zero torque position (45 deg) and continue to the 52 deg position. Magnetically, the rotor and stator poles attempt to stay aligned at the 45 deg position. This means the spring must "overpower" the magnetic torque to advance the rotor from the 45 deg position to the 52 deg position. This represents additional lost energy. The magnetic torque curve from 45 deg to 52 deg is a negative mirror image of the positive portion of the curve from 38 deg to 45 deg. Thus, the net energy for driving the rotor-cam assembly for one on-off pulse cycle (7 deg to 97 deg) is represented by the area (8.8×10^{-3} J) under the magnetic curve from 7 deg to 38 deg. Dividing this energy by 90 deg (in radians) gives a constant torque of 5.65 N-mm (0.80 in-oz) throughout the 90 deg total on-off stroke.

Spring-Cam

The solenoid torque-displacement curve of Figure 9 is determined by actual Instron test data. Using this data, a spring torque-displacement curve is derived by calculating data points such that the algebraic sum of the magnetic and spring torques for all displacements is equal to the above constant torque of 5.65 N-mm. The area under the spring curve from the start position to the spring "high center" position (7 deg to 42.4 deg) is used to determine the spring energy storage requirement. A spring is selected to meet this requirement with a reasonable (packageable) displacement. The 42.4 deg high center position is the point at which the magnetic torque has dropped to the calculated constant value of 5.65 N-mm. Beyond this point, as the magnetic torque continues to drop, the spring can no longer be stretched. Its torque must now start to aid the solenoid magnetic torque to maintain the constant output.

After the spring is selected, the cam follower moment arms are determined to meet the spring displacement requirement at one end, and give a reasonable cam size at the other end. Returning to the derived spring torque-displacement curve, incremental steps are considered along the displacement coordinate axis from 7 deg to 97 deg. Each increment defines a cam (and rotor) displacement and defines an incremental area (energy) change. With this energy change, a change in spring length is determined, which in turn gives a follower position, and this gives a new radial dimension for the cam. This radial dimension combined with the selected incremental angular displacement gives a polar coordinate point on the cam. Taking many increments along the displacement axis from 7 deg to 97 deg defines one lobe of the cam. This is repeated to give four lobes equally spaced at 90 deg.

Due to the solenoid and spring characteristics, the cam starts with a steep rise (high solenoid torque; low spring force) and levels off toward the high point of the cam (low solenoid torque; high spring force). On the "downhill" side of the cam (solenoid power off), the slope increases toward the end of the de-energized stroke to compensate for a weakening spring.

As noted earlier, the 52 deg rotor-cam orientation is a magnetic detent position at the end of the energized stroke. The "downhill" portion of the cam has an inflection point at this position, being steeper behind the inflection point than ahead of it. Behind 52 deg, the spring overpowers the rotor (which attempts to stay at the 45 deg pole aligned position) and rotates it to the inflection point. Ahead of 52 deg, the spring torque is weaker than the reverse magnetic torque, so further "overpowering" (advancement) is not possible. Thus, the follower stays at the inflection position as long as the solenoid remains energized. When it is de-energized the follower continues downhill for the de-energized stroke (from 52 deg to 97 deg).

CONCLUSIONS

The unidirectional solenoid provides the following stronglink improvements:

1. Volume is reduced 47%.

2. Enabling time is reduced 50% (1200 ms to 600 ms).

3. Useable energy per on-off pulse is increased from 3.46×10^{-3} J to 8.83×10^{-3} J. Since this provides two unique discriminator positions instead of one, this results in a 510% increase in energy efficiency.

The spur gear discriminator provides a more constant restraint on the safe-enable wheel, thereby enhancing safety. The use of a direct gear drive in place of the pawl-ratchet wheel mechanism should reduce wear, friction, and dynamic problems. Total piecepart quantities are reduced which should increase reliability and decrease costs.

Due to program budget cuts October 1, 1988, work on this project has been greatly curtailed. This has limited testing to bench runs of two prototypes plus Instron torque/displacement tests of two solenoids. A limited capability pulse generator has been fabricated to operate the prototypes. While this pulse generator cannot be adjusted to optimize the pulse format, it will allow additional data to be taken and facilitate the use of a high speed camera to study the dynamics of the device.

While testing has been minimal, results are encouraging. These results combined with development history of production components of similar complexity indicate this stronglink could be developed and used as a replacement component for future applications. Overall, this advanced development program has met its initial goals.

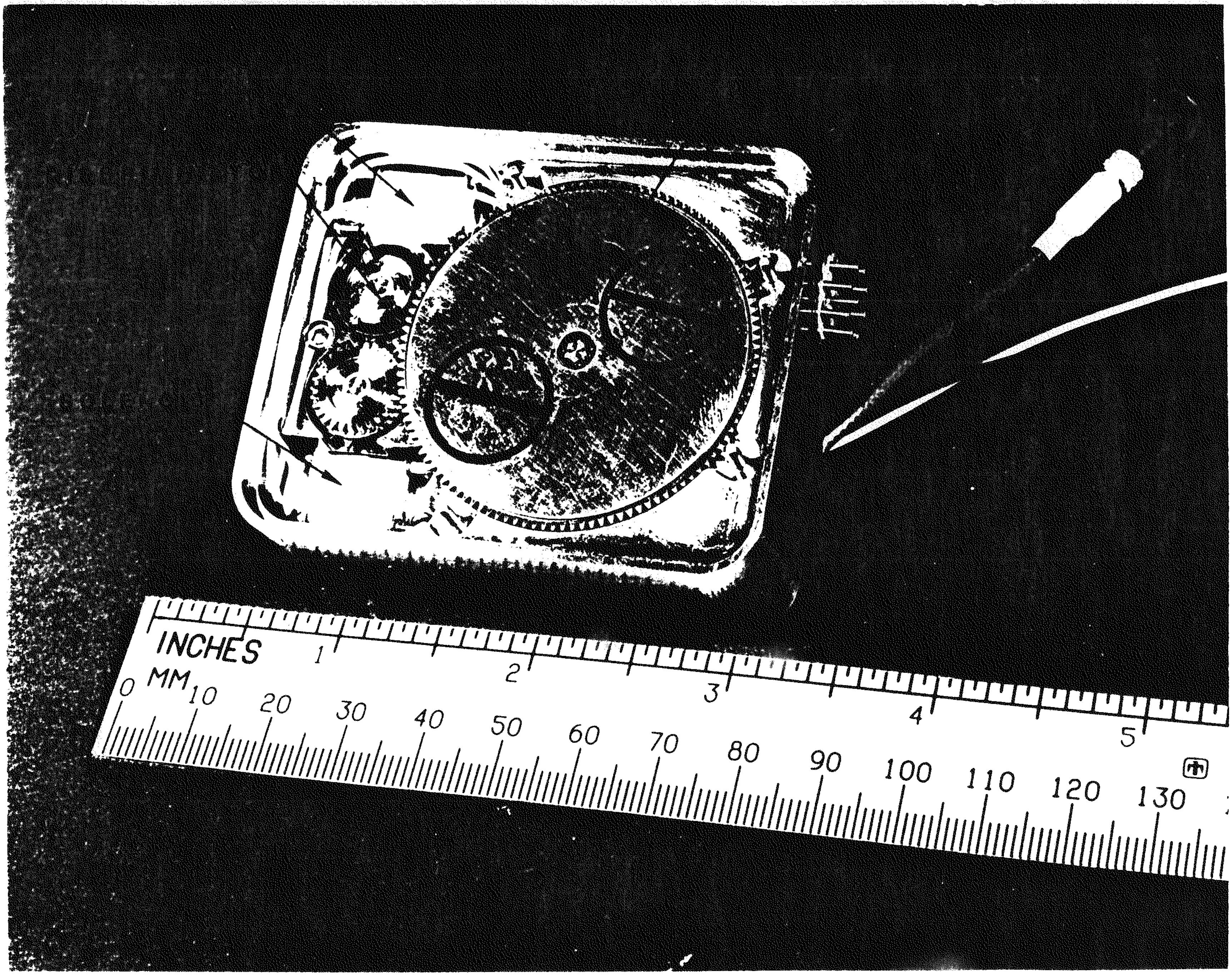


FIGURE 1. STRONGLINK ASSEMBLY

UNIQUE SIGNAL (UQS)

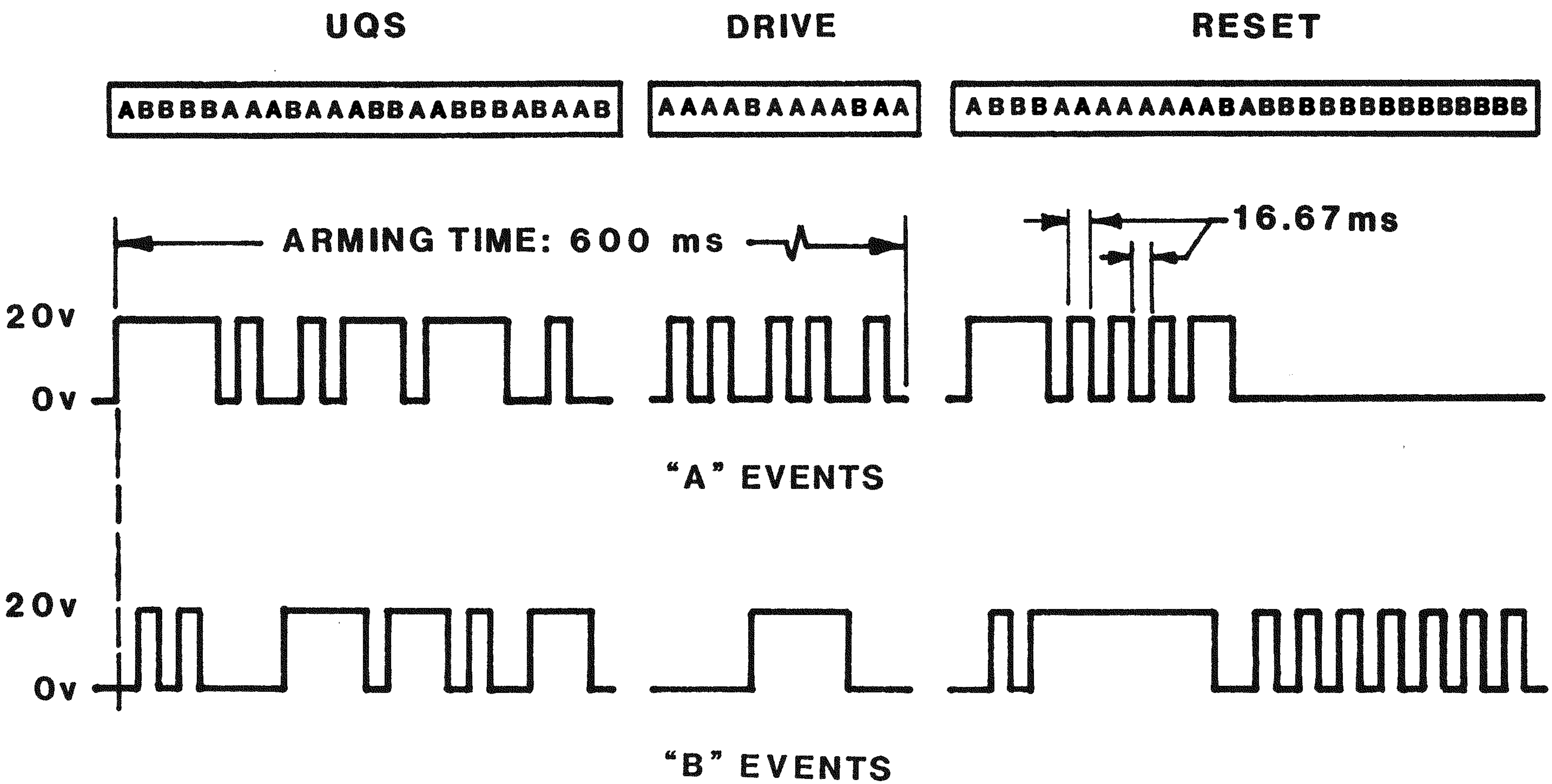


FIGURE 2. ELECTRICAL PULSE FORMAT

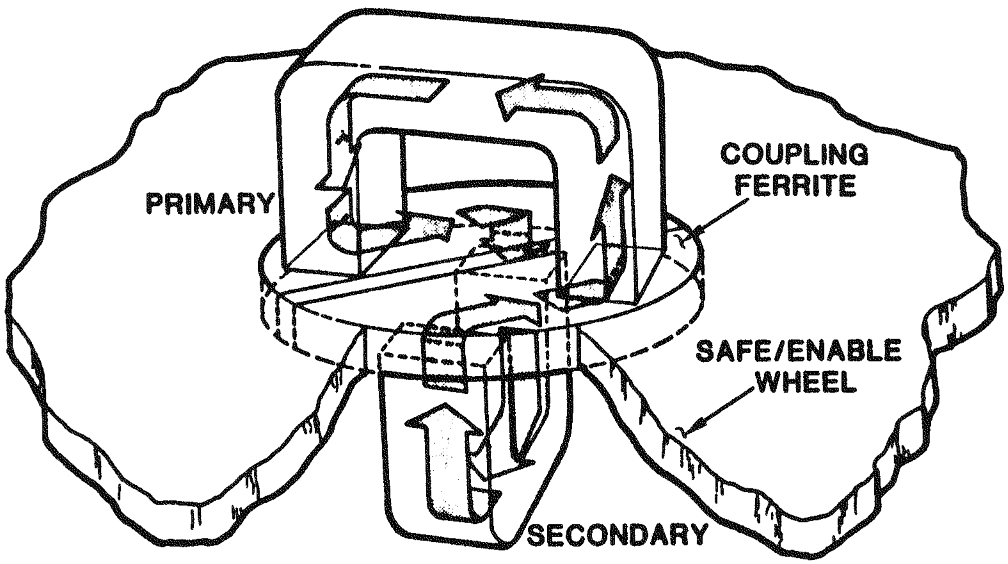


FIGURE 3. INTERRUPTED TRANSFORMER FLUX PATH (ENABLED)

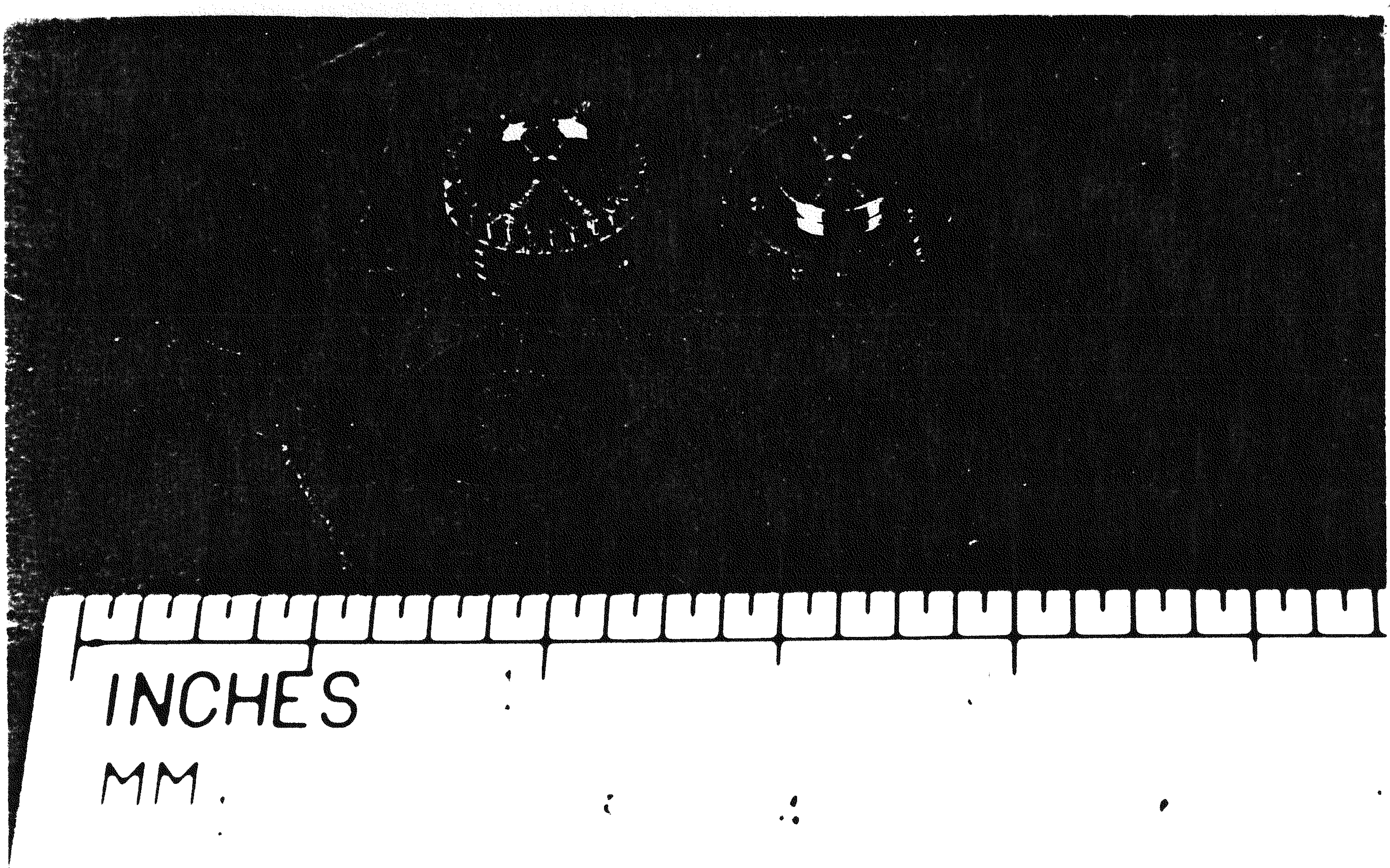


FIGURE 4. SPUR GEAR DISCRIMINATOR

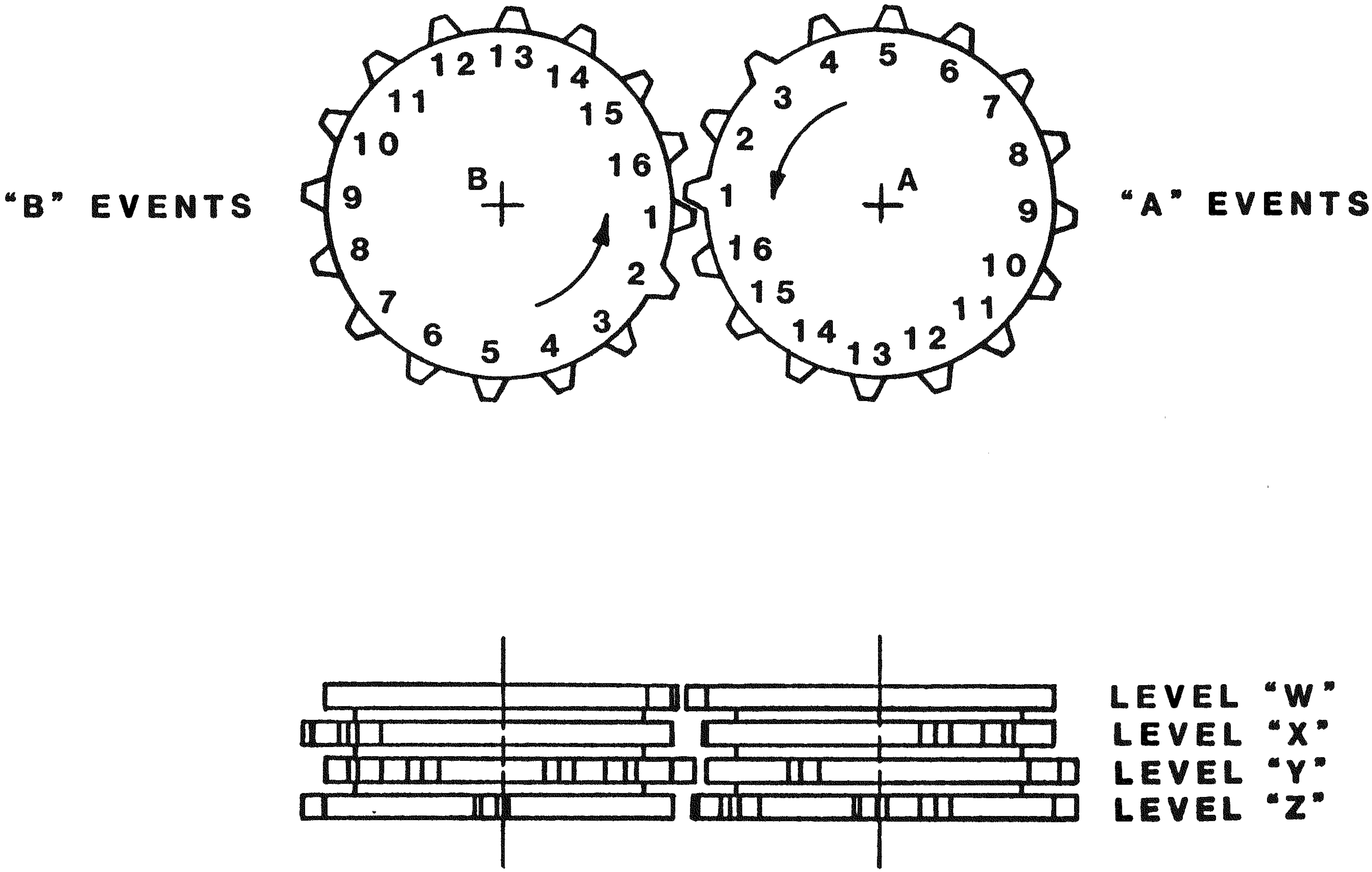


FIGURE 5A. SPUR DISCRIMINATOR ASSEMBLY

UQS: ABBBBAAABAAABBAABBBABAAB

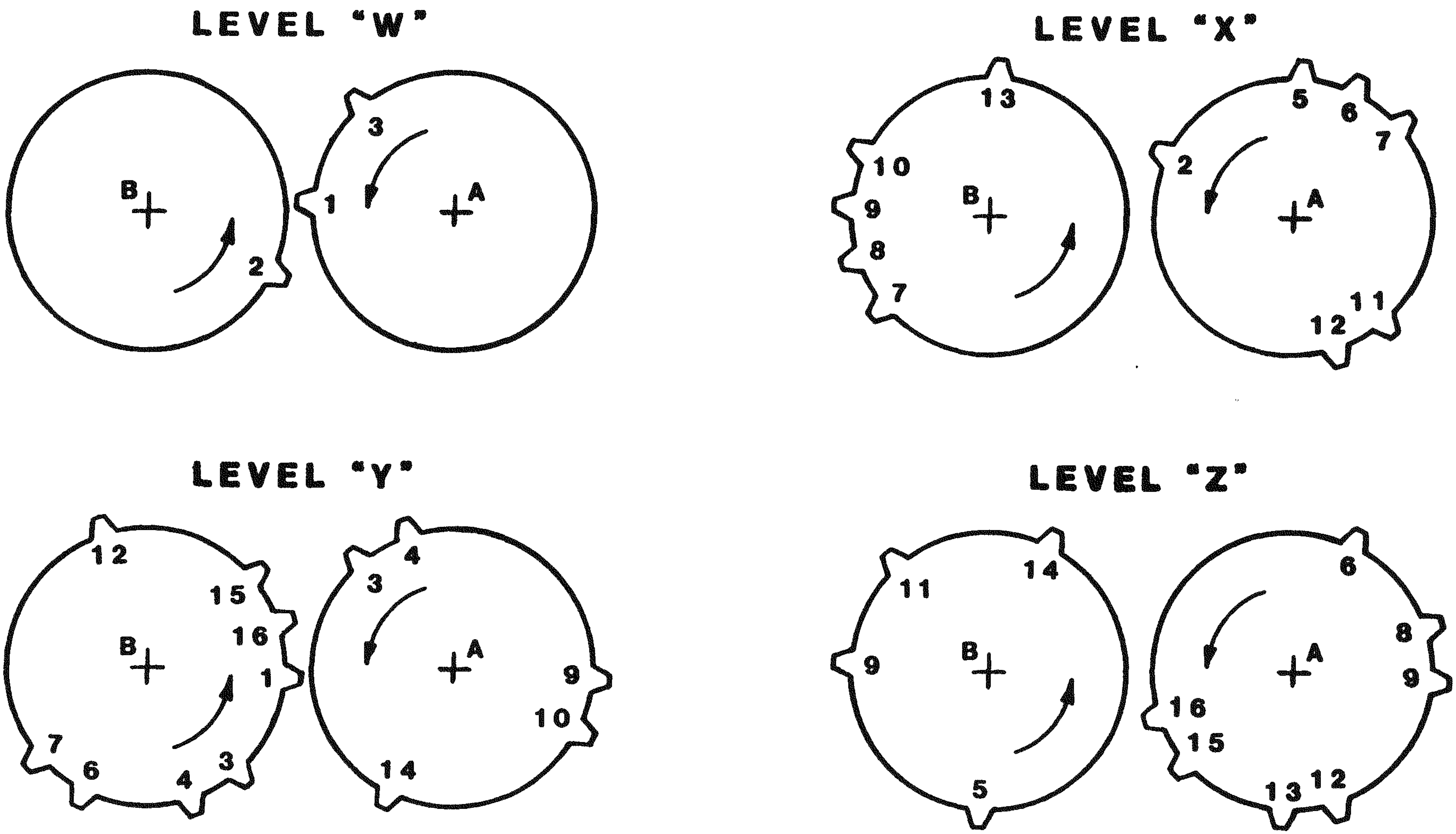


FIGURE 5B. GEAR SEGMENTS

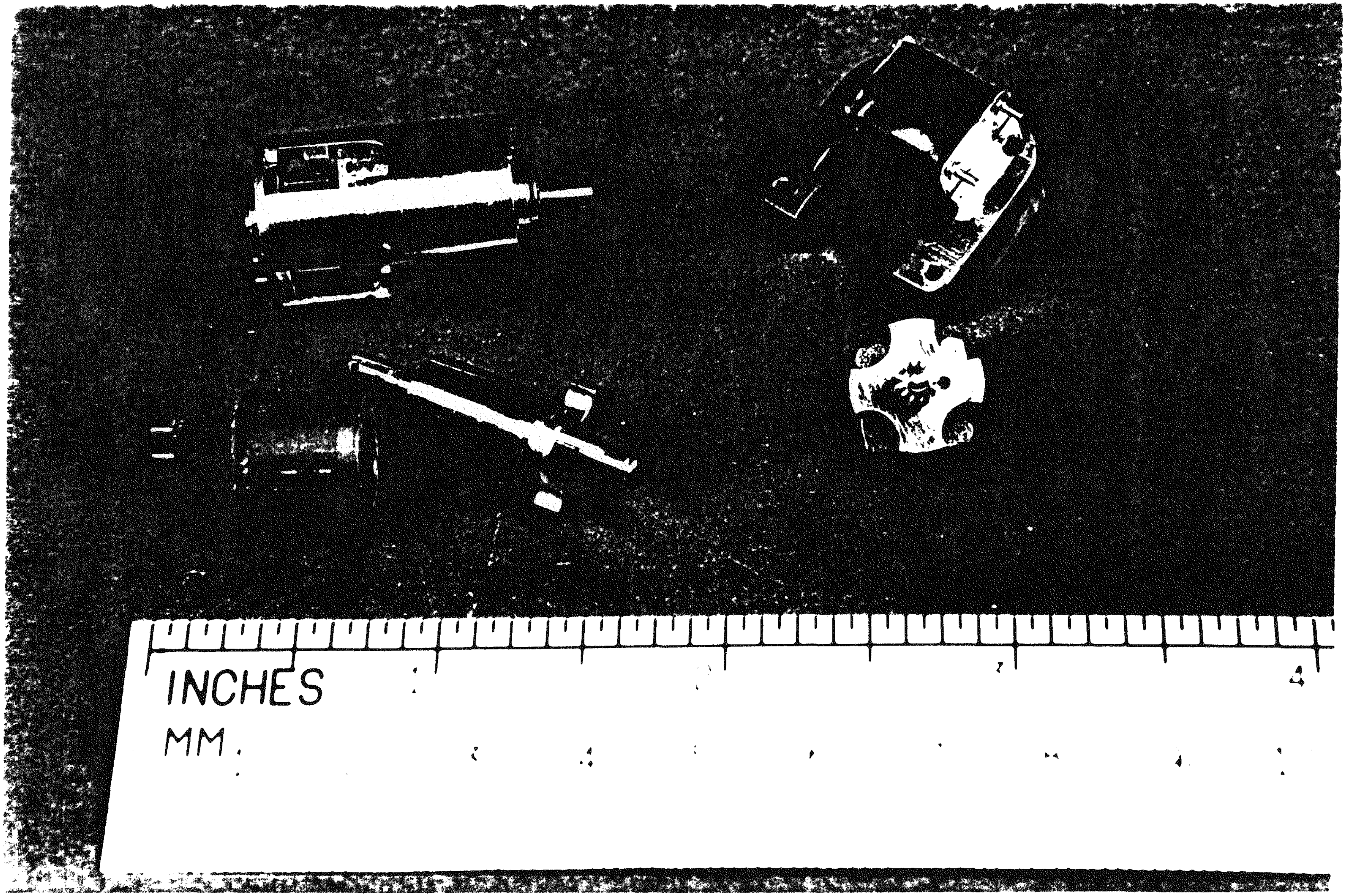
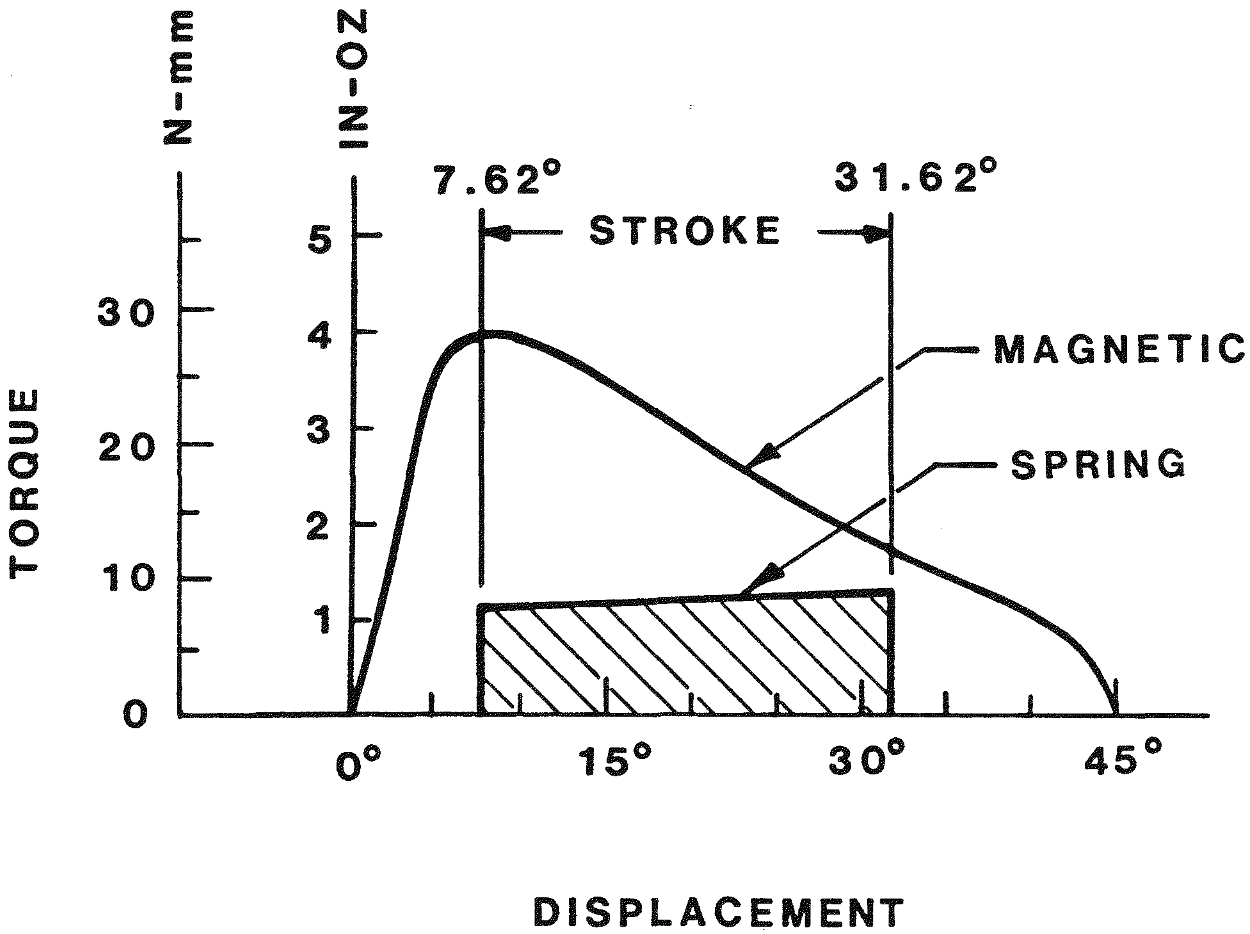


FIGURE 6. SOLENOIDS. OSCILLATORY (l), UNIDIRECTIONAL (r)



USEABLE ENERGY (SHADED AREA):

3.46×10^{-3} J(0.49 IN-OZ)

FIGURE 7. OSCILLATORY SOLENOID OUTPUT

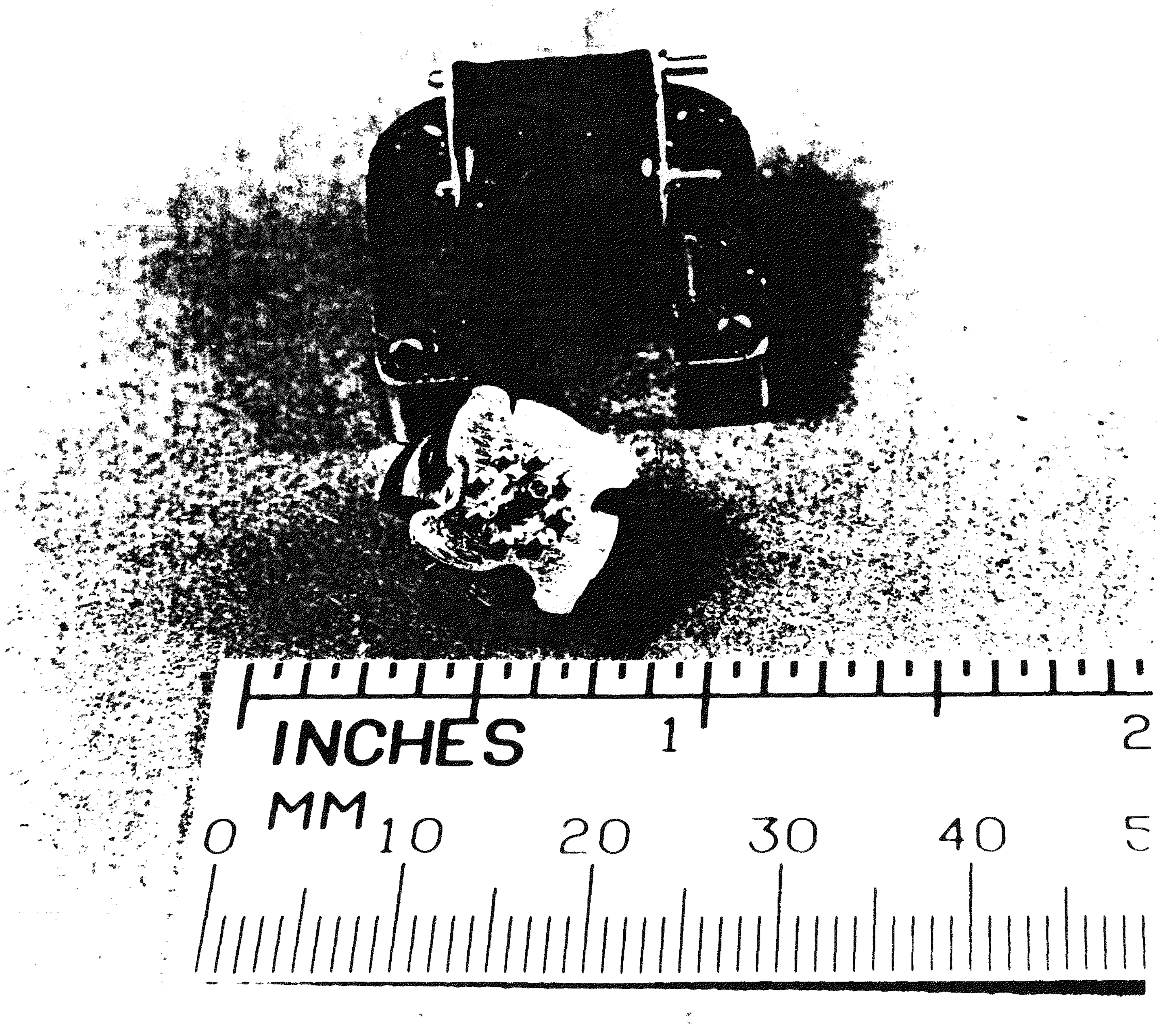


FIGURE 8. UNIDIRECTIONAL SOLENOID

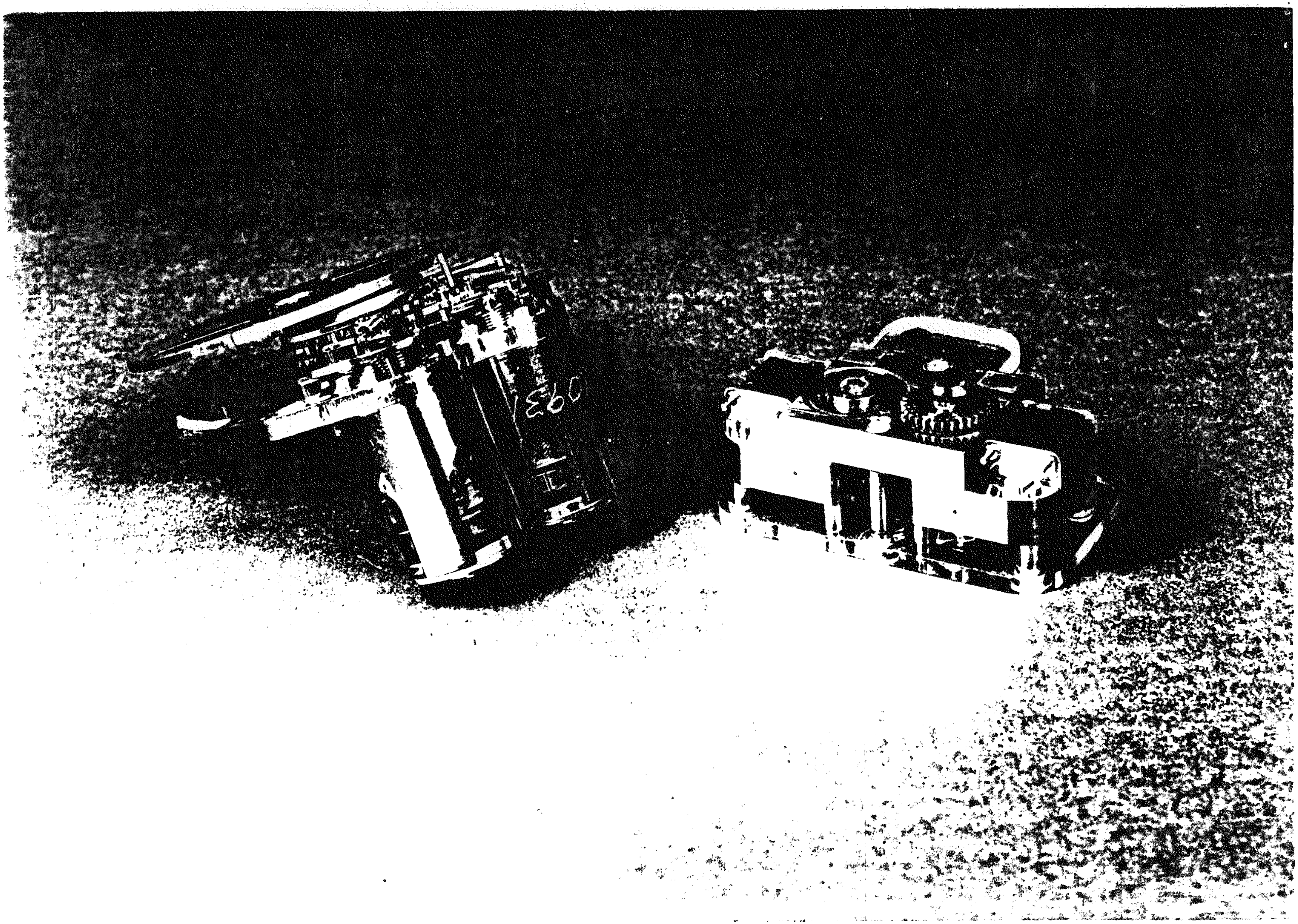
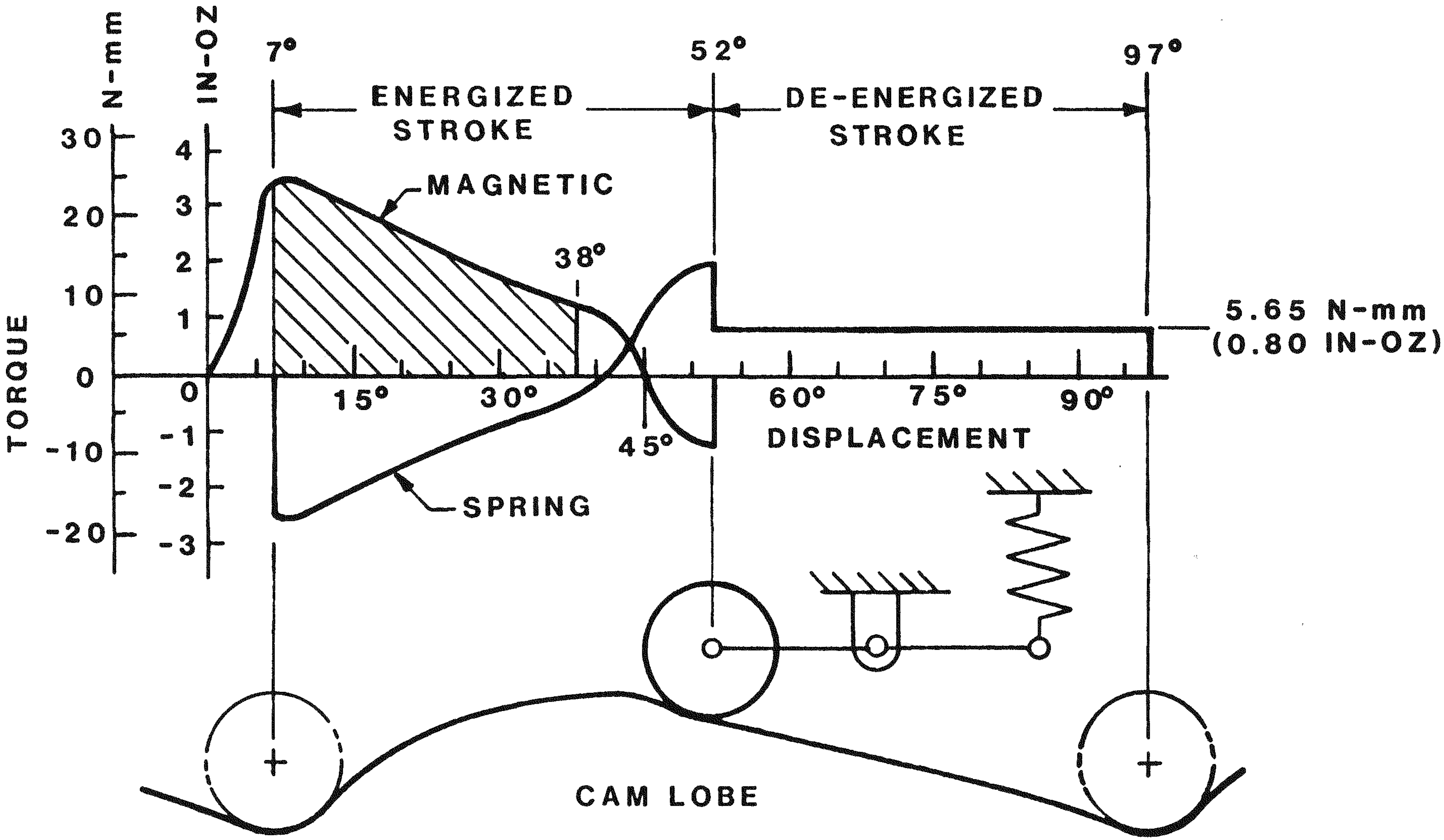


FIGURE 9. STRONGLINK MODULES. PRODUCTION (l), ADVANCED DEVELOPMENT (r).



USEABLE ENERGY (SHADED AREA): 8.83×10^{-3} J (1.25 IN-OZ)

FIGURE 10. UNIDIRECTIONAL SOLENOID OUTPUT