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THE SHAPED CHARGE CONCEPT, PART I. INTRODUCTION

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This article is a brief introduction to the concept of hollow charges and shaped charges. It is intended to be a tutorial to acquaint the novice with the basic principles of shaped charges, a concept which is not well understood by the layman. This introductory report will then pave the way for following articles which detail the history and applications of shaped charges.

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1. INTRODUCTION

Hundreds of documents have been written covering many aspects of shaped charges. However, due to the intense interest in this field by the defense establishments of many nations, a great deal of the literature is either limited distribution, classified, not available in English, or hidden in obscure government or industry documents. Also, certain industries (e.g., demolition, mining, oil exploration, etc.) that use shaped charge principles do not readily distribute information due to their highly competitive nature. This increases the number of proprietary and minimal distribution documents. In short, a great deal of information is simply not available to, or cannot be found by, even the most diligent researcher. In addition, these restrictions preclude discussion related to the design, behavior, and performance of shaped charges.

2. THE SHAPED CHARGE CONCEPT

A cylinder of explosive with a hollow cavity in one end and a detonator at the opposite end is known as a hollow charge. The hollow cavity, which may assume almost any geometric shape such as a hemisphere, a cone, or the like, causes the gaseous products formed from the initiation of the explosive at the end of the cylinder opposite the hollow cavity to focus the energy of the detonation products. The focusing of the detonation products creates an intense localized force. This concentrated force, when directed against a metal plate, is capable of creating a deeper cavity than a cylinder of explosive without a hollow cavity, even though more explosive is available in the latter case. This phenomenon is known in the U.S. and Britain as the the Munroe effect and in Europe as the von Foerster or Neumann effect.

If the hollow cavity is lined with a thin layer of metal, glass, ceramic, or the like, the liner forms a jet when the explosive charge is detonated. Upon initiation, a spherical wave propagates outward from the point of initiation. This high pressure shock wave moves at a very high velocity, typically around 8 km/sec. As the detonation wave engulfs the lined cavity, the material is accelerated under the high detonation pressure, collapsing the cone. During this process, depicted in Figure 1 for a typical conical liner, the liner material is driven to very violent distortions over very short time intervals, at strain rates of 10^4-10^7/sec. Maximum strains greater than 10 can be readily achieved, since superimposed on the deformation are very large hydrodynamic pressures (peak pressures approximately 200 GPa, decaying to an average of approximately 20 GPa). The collapse of the conical liner material on the centerline forces a portion of the liner to flow in the form of a jet where the jet tip velocity can travel in excess of 10 km/sec. Because of the presence of a velocity gradient, the jet will stretch until it fractures into a column of "jagged" particles.

When this extremely energetic jet strikes a metal plate, a deep cavity is formed, exceeding that caused by a hollow charge without a liner. Peak pressures in the metal plate of 100-200 GPa are generated, decaying to an average of 10-20 GPa. Average temperatures of 20-50% of the melt temperature and average strains of 0.1 to 0.5 are common. Localized temperatures and strains at the jet tip can be even higher. The penetration process occurs at strain rates of 10^6-10^7/sec. The cavity produced in the metal plate due to this jet-target interaction is due not so much to a thermal effect, but to the lateral displacement of armor by the tremendous pressures created (Figure 2). The target material is actually pushed aside, and the penetration is accompanied by no change in target mass, neglecting any impact ejecta or spall from the rear surface of the target.

The cavity formed becomes deeper when the explosive charge containing the liner is removed some distance away from the plate. This distance, for which an optimum exists (Figure 3), is called the standoff distance. Devices of this nature are called lined cavity charges or shaped charges.

The shaped charge was extensively used in World War II for penetration of hardened targets, i.e., tank armor, bunkers, and fuel storage containers. Today, it is employed for both military and peaceful purposes in the oil and steel industries; in geophysical prospecting, mining, and quarrying; in salvage operations; demolition work; as linear cutting charges for destruct devices in missiles; and for hypervelocity impact studies.

3. INTRODUCTION TO SHAPED CHARGES

The directional penetration effect observed when a hollow charge is detonated in contact with a steel plate is graphically depicted in Figure 4a. The crater depth is about 1/2 of the diameter of the hollow of the conical cavity. The cavity is produced by high pressure, high velocity gas erosion (the Munroe effect). When the hollow cavity is lined with a thin, hollow metallic or glass cone, the lined charge results in a much deeper crater as shown in Figure 4b. Furthermore, when the lined cavity charge is displaced from the target block some distance (known as the standoff), the penetration increases even more as depicted in Figure 4c.

The increase in penetration resulting from the lined shaped charge is due to the jetting process which occurs when the liner undergoes explosive-induced high-pressure, high-velocity collapse. The mechanism of jet formation for metallic conical liners with a semi-angle (one-half of the conical apex angle) less than 60^0 is as described below. Wide angle conical liners and non-conical liners are discussed in Walters and Zukas (1989).

Figure 5 shows a typical shaped charge configuration like that described above. Note that the explosive charge is not cylindrical, but tapered. This removal of some of the explosive weight is termed "boattailing" and does not affect the jet collapse mechanism. It is only necessary that the detonation wave front be symmetric about the longitudinal axis of the charge. A detonation wave that is plane and perpendicular to the charge axis-of-symmetry is assumed for simplicity.

When the detonator is fired, the detonation wave propagates through the explosive with the detonation velocity of the particular explosive used. When the detonation front reaches the conical liner, the liner is subjected to the intense pressure of the front and begins to collapse. The collapse is depicted in Figure 6 for the conical-lined shaped charge of the type shown in Figure 5. For the position of the detonation wave front shown in Figure 6, the upper (apex) region of the cone has collapsed and collided on the axis-of-symmetry. This collision results in liner material under tremendous pressure being extruded along the axis-of-symmetry, as described by D.R. Kennedy (1985), Evans (1950), Walters (1986), Walters and Zukas (1989), and Backman (1976). This extruded material is called the jet. When the pressures generated exceed the yield strength of the liner material, the liner behaves approximately as in inviscid, incompressible fluid. The cone collapses progressively from apex to base under point initiation of the high explosive. A portion of the liner flows into a compact slug, which is the large massive portion at the rear of the jet.

This preliminary jet formation theory was advocated by Birkhoff (1943, 1947), and the steady state, hydrodynamic theory of jet formation was formulated by Birkhoff et al. (1948). This hydrodynamic, steady state jet formation theory was first conceived by G. I. Taylor (1943) and Tuck (1943), independently by Birkhoff (1943), and by Schumann (1945) and Schardin (Simon 1945) in Germany. The shaped charge jet collapse mechanism described above was verified by the early flash radiograph studies of Clark et. al. (1945, 1949), Seely and Clark (1943), Tuck (1943), Schumann (1945), and Schardin (Simon 1945). These radiographs proved earlier theories of jet formation to be invalid. The earlier theories claimed that the penetrating jet was due to either a focusing of the detonation gases, the formation of multiple, interacting shock waves, the spallation of the liner material, or some combination of these effects, including the theory that jets of gas (from the detonation products) break through the metallic liner and carry fragments resulting from the rupture and erosion of the liner. An interaction of these jets then causes a strong forward wave which imparts a high velocity to the liner particles. Birkhoff (1947) and George (1945) discuss these early theories since discredited by the early flash radiography data. The theory of jet formation for shaped charge liners which display different collapse mechanisms, e.g., plastic flow or extrusion, spherical convergence, or brittle fracture, are described by Poulter and Caldwell (1957).

In fact, the shaped charge concept is not well understood by people outside the science of ordnance devices. For example, a shaped charge jet is not a "cutting plasma" and does not "burn its way through the armor" as reported by Lawton (1986), Aronson (1986), and Schemmer (1987). The jet from a shaped charge is not a "molten metal slug" as report by Budiansky et al. (1987). Also, D.R. Kennedy (1985) addressed this issue and stated that probably nine of 10 descriptions of shaped charge HEAT projectile functioning are in error. (See Kennedy's [1985] references 6, 21, 27, 30, 31, 33.) The acronym "HEAT" stands for High Explosive Anti-Tank and does not relate to thermal effects.

A rough analogy to the jet formation can be drawn to the effect produced when a sphere is dropped into water. During impact and downward motion in the water, the cavity formed moves outwards around the sphere and then reverses to collide along the axis-of-symmetry. On collision, vertical jets are formed, which squirt upwards and downwards (Evans 1950; Birkhoff 1947; and Worthington 1908).

Crude "rules of thumb" were established by Evans (1950). Namely, about 20% of the inner surface of the metal of the cone is used to form the jet. The jet diameter is about 1/20th of the diameter of the cone. The jet tip velocity is of the order of the detonation velocity of the explosive. The jet velocity decay is a nearly linear function down to about 1/4 of the detonation velocity at the tail (rear) of the jet. The velocity of the slug is of the order of 1/10 of the jet tip velocity. These values are only crude order-of-magnitude estimates and are only for moderate apex angle, copper, conical liners. Techniques that provide more accurate estimates of the jet and slug parameters are available (Walters and Zukas 1989). Also, the jet formation is strongly dependent on the liner geometry, liner material, high explosive geometry, confinement geometry and material (if confinement is present), the type of high explosive used, and the mode of initiation. In any case, the goal is to direct and concentrate energy in the axial direction to enhance the damage resulting from the hollow charge.

For any liner design, a proper match between the charge to mass ratio (explosive charge mass to liner mass ratio) is critical. If the liner is too thick, the energy losses resulting from internal friction and heating of the liner walls during the collapse, and the energy losses due to spallation of the thick liner, will reduce the collision velocity below the value necessary for jet extrusion. Also, if the liner wall thickness is too thin, directed flow is not achieved, due to the loss of structural integrity of the liner. If the wall is extremely thin, the liner material may undergo vaporization upon collision.

Shaped charges with wide angle cones or hemispherical liners show a radically different collapse pattern. Hemispherical liners invert (or turn inside out) from the pole, and as the detonation wave progresses toward the base of the liner, the hemispherical liner approximates a conical liner, and the inverted collapse pattern reverts to that of a cone. In general, the hemispherical and large angle conical liners usually result in larger diameter and lower velocity gradient jets. No massive slug, per se, is formed. Poulter and Caldwell (1957) discuss some alternate collapse theories, but do not address point-initiated shaped charges with hemispherical liners.

Of course, jet effects or controlled fragmentation are not limited to conical or hemispherical liners. Extensive use has been made of other liner designs as well as linear and circular charges. The liner cross sections for linear and circular charges are wedges and semi-circular configurations, respectively. The jet produced by a linear charge is in the form of a thin ribbon, and in the case of a circular (torus) charge, a tubular spray (Mohaupt 1966). A linear charge and a circular or torus charge are illustrated in Figure 7.

4. THE NOMENCLATURE

The shaped charge ordnance community has its own unique nomenclature as shown in Figure 8. An explosive train, consisting of a detonator, booster, and the secondary high explosive (HE) fill is shown. In the figure, a conical liner is illustrated. The liner diameter (LD) is the outer diameter of the liner. The liner is encased in the cylindrical explosive billet, which has a charge diameter designated as CD (and not to be confused with the cone diameter, as sometimes happens). In this illustration, the LD is less than the CD, or the liner is said to be subcalibrated. If the charge is confined in some type of case (either to assist in casting the high explosive, to provide fragmentation effects, or to enhance the shaped charge performance), the outer diameter of the case is termed the warhead diameter (WD). The overall length of the device is termed the charge length (L), and the length of the explosive fill between the apex of the liner and the booster is called the head height. Finally, the distance from the base of the charge to the target is called the standoff distance, or simply the standoff. The effective standoff, or virtual standoff, is the distance from the virtual origin of the warhead to the target. The virtual origin is the point from which the shaped charge jet can be assumed to originate, and is discussed in Walters and Zukas (1989).

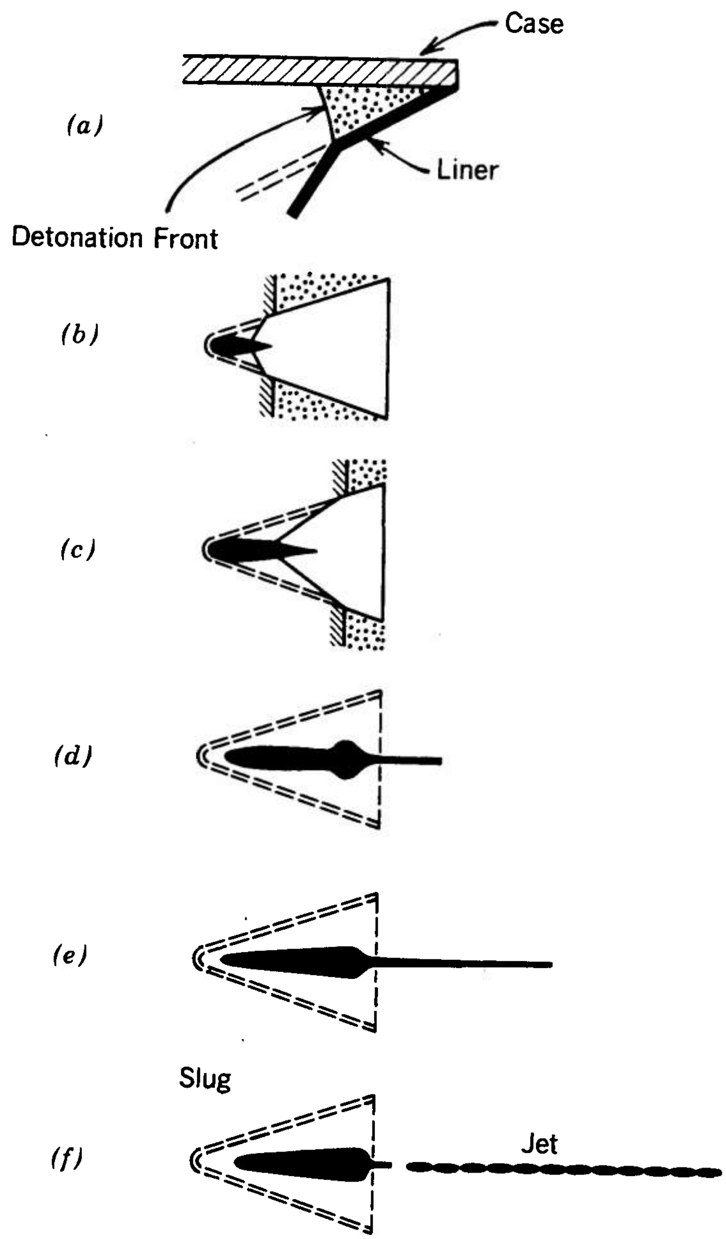


Figure 1. The Collapse of A Shaped Charge With A Conical Liner (Walters and Zukas 1989).

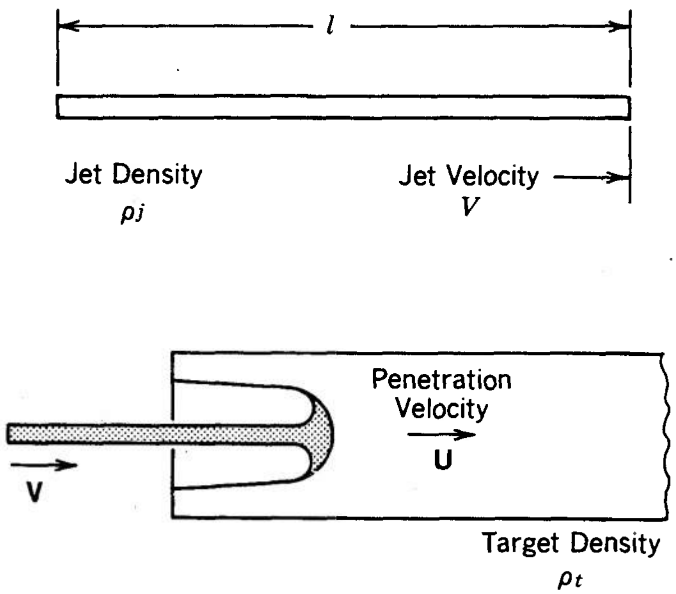


Figure 2. Jet Penetration (Walters and Zukas 1989).

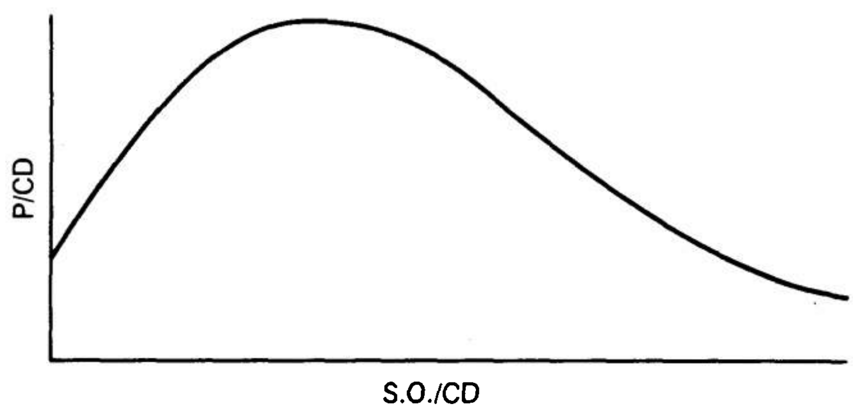


Figure 3. Penetration-standoff Curve for a Conical Shaped Charge Liner (Walters and Zukas 1989).

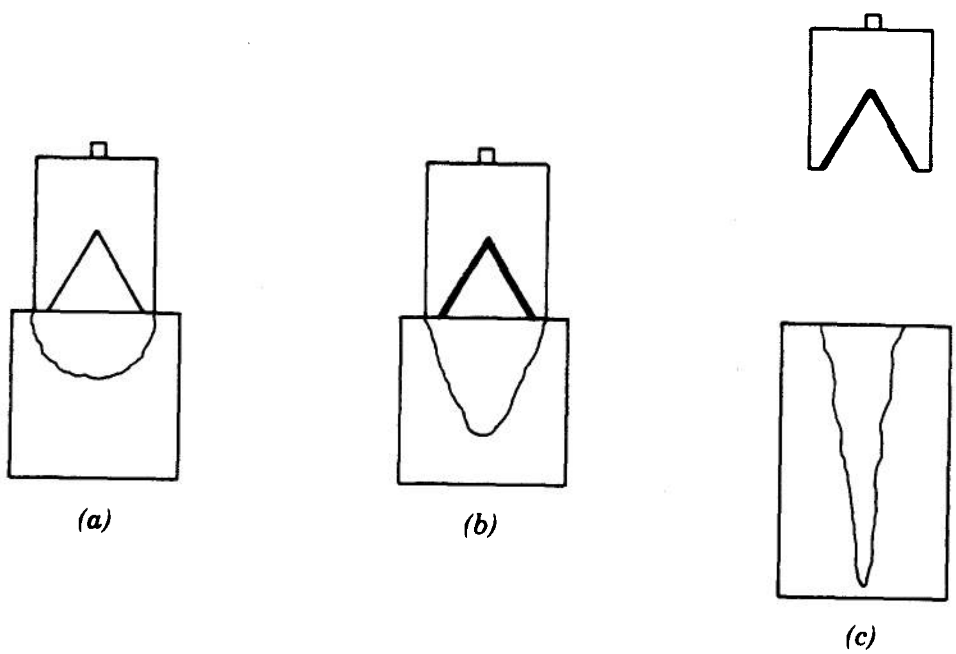
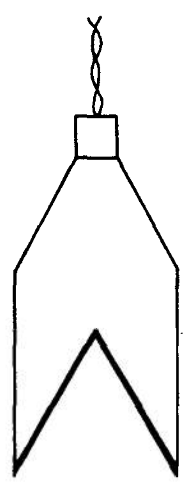


Figure 4. The Lined Cavity Effect (Walters and Zukas 1989).

Figure 5. Typical Shaped Charge Configuration (Walters and Zukas 1989).



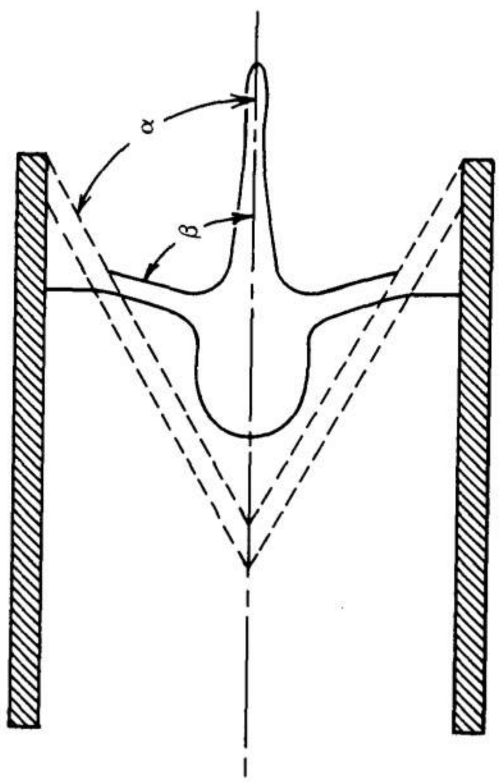


Figure 6. Schematic Collapse of a Typical Shaped Charge With a Conical Liner (Walters and Zukas 1989).

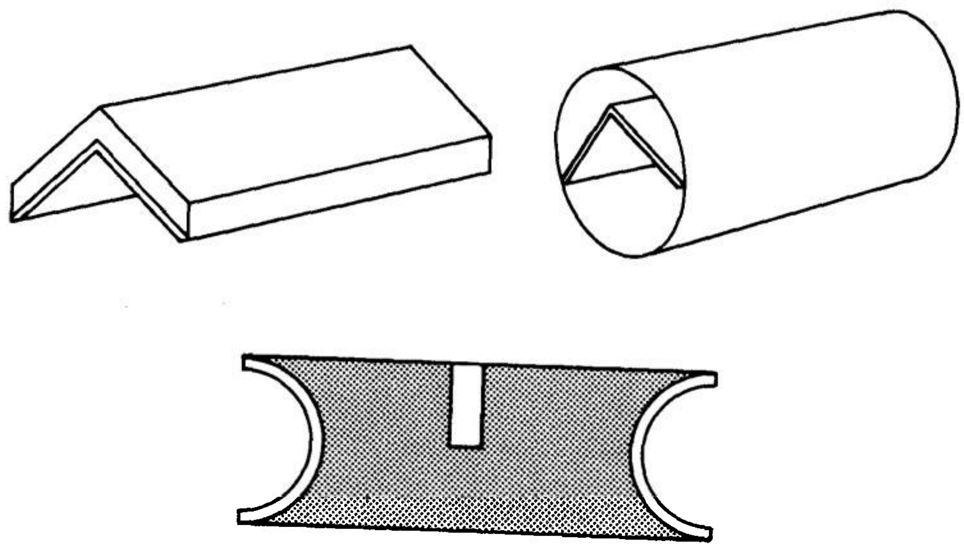


Figure 7. Linear and Circular Lined Shaped Charge Configurations (Mohaupt 1966).

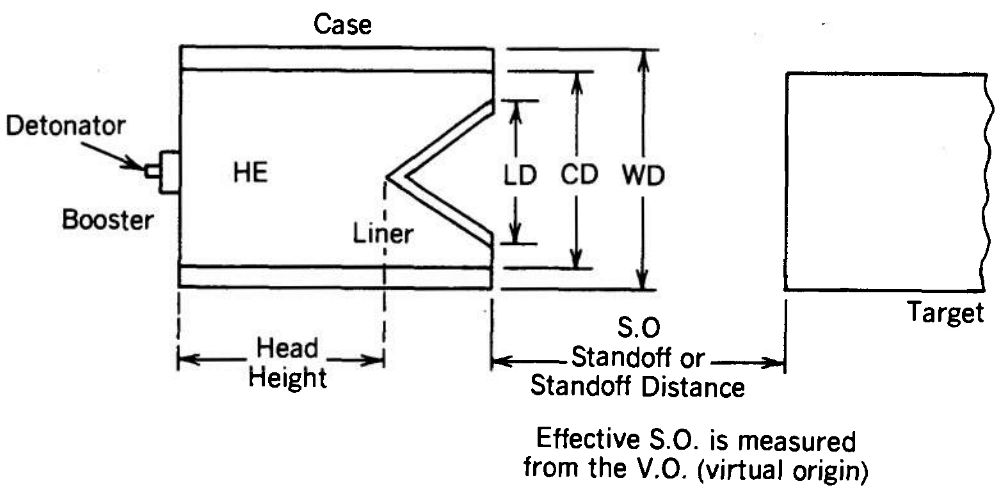


Figure 8. <u>The Nomenclature for a Shaped Charge Configuration (Walters and Zukas 1989)</u>.

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