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UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 77

A New Facility for Eval ation of Materials Subject to Erosion and Cavitation Damage

by
JOHN F. RIPKEN, JOHN M. KILLEN,
SCOTT D. CRIST
and
ROY M. KUHA

Prepared for
OFFICE OF NAVAL RESEARCH
and
DAVID TAYLOR MODEL BASIN
under
Bureau of Ships General Hydromechanics Research Program
S-R009-01-01
Contract Nonr 710(56), Task NR 062-334

March 1965
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PREFACE

Despite the development of many devices for study of the failure of materials exposed to cavitation or fluid erosion, a need has existed for a facility which would permit a more fundamental study of the damage mechanism. Fundamental studies which can lead to naval design procedures providing reduced erosion are essential to modern naval interests.

Studies leading to the development of the new facility described herein were carried out at the St. Anthony Falls Hydraulic Laboratory during the period from January, 1964 to March, 1965 under the joint sponsorship of the David Taylor Model Basin and the Fluid Mechanics Branch of the Office of Naval Research.

ABSTRACT

A new type of test facility for simulating accelerated cavitation damage is described. The facility consists of a rotor with a material specimen attached at the periphery in such a manner that there is repeated impact with a column of liquid droplets during high-speed rotation of the specimen.

Preliminary tests indicate that weight loss from a specimen due to erosion follows the same trend as that produced in cavitation damage facilities. Enhanced ability to control impact conditions in this facility permits detailed study of the mechanics of failure.

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A NEW FACILITY FOR EVALUATION OF MATERIALS SUBJECT TO EROSION AND CAVITATION DAMAGE

I. INTRODUCTION

For nearly forty years various investigators have attempted to develop and routinely employ test procedures which would realistically evaluate the service resistance of fabricated materials exposed to erosion by water impact. These evaluations were necessary for the design selection of materials for steam turbine blades, for hydraulic machinery, and more recently for underwater ship appendages and for aircraft windshields.

Early studies of damage demonstrated the difficulties in attempting to make evaluations on the basis of field tests. As a result field testing has largely given way to simplified and accelerated testing in the laboratory. In the case of steam turbines this has been accomplished with whirling blades impacting high-speed jets. Studies of aircraft rain erosion have also used whirling blades in a spray and, for higher speeds, a projecting of fluid slugs at stationary solids or firing solids at stationary drops of liquid. For hydraulic devices and ship members exposed to cavitation, the accelerated test apparatus has varied widely, but three basic types have found considerable use. These are the Venturi throat or recirculating tunnel, the vibratory apparatus, and the submerged rotating disk with cavitating perforations.

Cavitation damage studies in the three named types of devices show a general similarity of findings, but a number of significant differences continue to appear in the quantitative values derived from the various test programs. The findings and differences in these studies have yielded a number of pertinent questions which include the following:

1. Is there a threshold value of the relative flow velocity at which damage begins on a given material; or is damage a combined function of the frequency and intensity of the impact being delivered as a result of the velocity?
2. Is there an "incubation" period of exposure during which little or no evident damage occurs but which is eventually followed by substantial erosion when the exposure condition persists?
3. Are there a number of cycles of increasing and decreasing rates of damage with time as observed

by Hammitt [1]* or is there a simpler, progressively increasing rate as observed by Lichtman et al [2]? Are these later stages of damage simply a byproduct of the flow disturbances caused by the earlier stages and thus a function of the particular test environment? Should these later stages be omitted in a fundamental damage evaluation?

4. The rate of weight loss attributable to damage appears to be a function of some relative fluid velocity raised to the n^{th} power. Is this power the fourth, fifth, sixth, or eighth as observed by various experimenters? Will the ultimate velocity limit of all shallow depth underwater naval operations be keyed to this relation?

5. To what extent can the elasticity, fatigue, hardness, strain energy, roughness, thickness, or other characteristics of the material be correlated with the observed damage? Will the strain energy correlation of Thiruvengadam [3] prove to have wide-ranging application or will additional properties be required in the correlation as suggested by Hammitt et al [4]?

6. To what extent do the density, viscosity, surface tension, chemical, or other characteristics of the fluid influence the damage?

While a study of the literature indicates a present ability to make suitable material selections for many design problems and provides partial or qualified answers to many of the foregoing questions, there is substantial evidence that:

a. Naval operations will be continually plagued by cavitation problems as the trend toward increased speeds continues.

b. Existing types of damage facilities are inherently incapable of providing suitable definition to the fundamental mechanism of cavitation damage.

The prime difficulty with the existing test systems for accelerated cavitation damage lies in their inability to provide adequate experimental control over the many variables that are concurrently involved in the cavitation damage phenomenon. This suggests that the control problems might be greatly simplified by eliminating the complex and obscuring parts of the phenomenon that have to do with the creation of the cavity, and by concentrating instead on

*Numbers in brackets refer to the List of References on page 13.

the erosion mechanism associated with cavity collapse. That this is a realistic approach is supported by the opinion of many investigators as summarized by Eisenberg [5] who shows evidence that the principal mechanism of cavitation damage is the mechanical destruction of the solid surface by the localized impact of the surrounding fluid.

The facility described herein strips the collapse phenomenon to its bare essentials by examining the erosion action of an impacting fluid element on a boundary solid. This is done in a system which minimizes the variables and establishes a good control of those which remain. This approach by no means discounts the importance of continued studies of the more complete cavitation model but instead aims to aid in clarifying the study of erosion or damage by concentrating on the most pertinent and fundamental elements of the mechanism.

That some simplification is possible may be seen from a study of previous steam turbine blade erosion tests and the windshield rain erosion tests which have employed fluid impact systems which are much simpler than those employed in cavitation studies. While gross fluid jet impact studies were used many years ago by Rheingans [6] to simulate cavitation damage for materials selection, the method was abandoned in favor of the seemingly simpler vibratory test. Abandonment was to a considerable extent based on a lack of evidence showing that cavitation damage is basically the product of a fluid jet impact erosion mechanism. Jet impact as a damage mechanism now appears to have some substance as a result of the work of Ellis, Naude, Plesset, and Mitchell [7][8][9] at the California Institute of Technology. The CalTech work has, by high-speed photography, served to show that cavities collapsing near boundaries collapse unsymmetrically with the formation of a reentrant jet or interface front which moves through the cavity to impinge on the solid boundary. The physical observations by Ellis have shown that the jet velocities are of a damaging order of magnitude and that the shape of the jet tip is probably significant to the pressure developed on the boundary.

Currently studies of damage on steam turbine blades are made with sample pins or blocks attached to the periphery of a disk rotating in air at high speed. A recent version of this type of facility has been employed also for material evaluations for cavitating hydraulic machinery [10]. In this type of test fluid impact is achieved on the sample by continuous injection of a high-speed water jet positioned with its axis parallel to the disk shaft and passing between the rotating damage samples. By this mechanism a fluid element of substantial mass impacts on the sample at high frequency (several hundred per second) and with high velocity (up to 1000 fps). The resulting damage rate is very high. The device has produced interesting results but is not considered suitable to fundamental studies because of an inherent inability to independently control the frequency and velocity of impact and to control the geometry of the jet front which initially impacts on the solid. The high damage rates in these tests quite probably relate to grossly abnormal thermal, chemical, or electrical effects as well as to high stressing. These secondary effects might be quite different for elastomers or plastics than they are for metals and must be brought under control in any fundamental study.

The windshield erosion studies have even further simplified the fluid impact test mechanism by either firing a solid sample at a stationary droplet [11] or by projecting (up to 4000 fps) a fluid slug at a stationary solid [12]. The first method has permitted some control of the shape and size of the fluid interface and of the impacting velocity but only in single impacts. It does not permit measurement of impact pressure transients. The second method permits measuring transient pressures in the solid but does not permit refined control of the jet size or shape because of the inherent instabilities of an interface under dynamic conditions. More important perhaps is the inability of these systems to produce the repetitive impacts which are basic to the fatigue failures which are believed fairly common with cavitation damage. These two methods together have, however, served many of the needs of rain erosion studies in that these studies are generally concerned with single impact failure for droplets impinging on thin plate structures at supersonic speeds.

The foregoing methods were not considered directly applicable to simulating cavitation damage, but they did serve to point the way to a modification which appears to be a workable compromise. This modification consisted of designing an apparatus in which a drop of slow moving water would impact on a small target of test material moving at a high velocity. The mass of the impacting liquid and the velocity of impact were to be rather readily and accurately controlled, and controlled rates of impact repetition were to be provided.

The resulting experimental equipment described herein produces many drops of water of a selected uniform size and introduces them into the path of a target of test material mounted on a rotating arm. The introduction of the drops into this path is controlled with precision to subject the same point on the target to repetitive blows at a selected impact speed.

II. EXPERIMENTAL APPARATUS

The basic facility consists of a rotor with a material specimen attached at the periphery in such a manner that there is impact with a column of liquid droplets during rotation of the specimen.

The aluminum alloy rotor as shown in Fig. 1 consists of two central disks supporting two projecting arms, the tips of which contain mounting sockets for the test specimen as shown in Fig. 2. The specimen rotates in a circle of 23.68 in. diameter at a present maximum rpm of 12,000 giving a tangential speed of 1,250 fps. (It is anticipated that future changes will permit increasing the speed to 1,500 fps or more.) Speed is infinitely adjustable down to the minimum values of interest of about 400 fps. The specimen has a target face of 1/4 in. diameter as shown in Fig. 2. A small target volume of about 1/8 cc favors sensitive weight loss determinations. The tapered target is mounted in a tapered recess in the rotor arm and is drawn snug with a draw screw tapped into the rear of the target.

The rotor is spun within a protective chamber by a variable speed, directly connected, electric motor of 1 hp. The motor is a type commonly employed in vacuum cleaners. An auxiliary motor and blower are employed for cooling the drive motor. The general assembly is shown in Fig. 3 in the closed condition used for testing and in Fig. 4 in the open position used for changing test specimens.

The drive system is patterned after systems successfully employed with ultra-centrifuges [13]. The drive shaft is a 1/8 in. diameter stainless steel tube gripped by collets mounted on the motor shaft and on the rotor. The tube provides flexible coupling which permits the rotor to find its own center of rotation without elaborate dynamic balance procedures. This also permits a very smooth high-speed operation even after loss of target material. This stability is quite important for photographic purposes. It has been found possible to superimpose nearly 4000 exposures on a single film without loss in desirable sharpness of the target or drop.

Starting is a problem in this flexible system for speeds up to 300 rpm. A teflon guide bearing is provided to limit the undesired motions of the rotor in this speed range. As soon as the first critical is reached, the rotor spins smoothly and no longer touches the guide bearing.

The chamber pressure around the rotor is reduced to 0.01 atmosphere by continuous vacuum pumping. This is necessary to reduce the aerodynamic drag of the rotor and to reduce the wind disturbance on the drops which are introduced into the target path.

The vacuum seal for the drive shaft is a close fitting babbitt sleeve approximately 1 in. long which is positioned over a hole in the chamber cover. It presses against an "O" ring at the bottom to provide a vacuum seal. Oil is fed continuously into a cup at the top of the sleeve to provide a liquid seal for the shaft. An oil slinger and catch cup on the shaft below the sleeve removes the oil before it is scattered throughout the chamber.

The small drops of water needed for target impacting are generated in the bell jar above the main housing chamber shown in Figs. 3 and 4. The drops are produced by attaching a fine glass capillary nozzle in axial alignment with the vibratory dome of a speaker element. A number of devices of this type are reported in detail in the literature [14][15]. The test liquid flows through the capillary nozzle from a reservoir and is valve controlled. Because of the forced vibrations, the liquid discharges in a discrete series of droplets directed vertically downward through a small hole in the top of the main housing chamber. Flow in the capillary is induced by the pressure difference which exists between the reservoir at atmospheric pressure and the capillary nozzle which is in the evacuated bell jar. A shutter deflects the drops away from the impact area or allows them to strike the target as desired. Current tests have been conducted with drops of 0.047 in. diameter, but substitution of other nozzles will permit other size selections. The system readily provides electronic count of the number of test impacts.

The signal to drive the vibrating capillary is derived from a photoelectric pickup and a slotted wheel mounted on the rotor. The best drop production seems to occur between 600 and 1000 cycles per second. This range is determined by flow rate and jet diameter and is given in Refs. [14] and [15] as $7a < \lambda < 14a$ where a is the jet diameter and λ is a wave length based on jet velocity and vibrator frequency. The number of slots on the "pickup wheel" must be determined by the wave length criterion and by the desired rotational speed. Some flexibility was introduced by feeding the output of the photoelectric cell into a General Radio tone burst generator. This instrument counts a preset number of pulses and switches from one stable state to the other. In this way a square wave is generated which is an accurate submultiple of the output frequency of the photoelectric pickup.

The output of the tone burst generator is then fed to an audio amplifier and then to the speaker element of the bubble generator. The particular wave form driving the drop generator seems to have little influence on the bubble production.

The position of the bubble as it impacts the target is controlled by the phase of the electrical signal with respect to the rotor position and the rate of flow of the liquid to the capillary. The vacuum in the chamber is the force moving the liquid through the capillary. Flow rate is controlled by a pinch clamp on the supply tube. The electrical phase control is adequate for long term tests; however, the flow control must be continuously monitored.

Two small windows in the protective chamber permit viewing the moving target in either full face or profile. Illumination is provided by a General Radio Strobotac which is synchronized with the motion of the rotor with a second photoelectric pickup and slotted wheel.

It has been found necessary to pack the bottom of the protective chamber on the outside with dry ice to promote condensation and thus reduce fogging of the viewing windows with spray and to reduce disturbance of the bubble stream by the swirling spray.

The present system permits investigation of a large number of impacts. It seems possible, however, to be able to employ an electrostatic deflection system on the drops [14][15] so as to selectively position any number of drops in the impact area down to a single event.

III. EXPERIMENTAL PROCEDURE

The application of the device to date has been limited to a brief series of tests intended to show the capabilities of the test apparatus.

A representative number of metals were selected and machined into the sample form as shown in Fig. 2.

The equipment was adjusted so that the center of the sample face would impact a liquid drop on each revolution. Four test speeds were arbitrarily selected at 500, 750, 1000, and 1250 fps.

A simple measure of weight loss as affected by exposure time was made by stopping the apparatus periodically and removing and weighing the sample. It was possible to watch the progress of the erosion visually with a small telescope. This was of great help in establishing the increment of exposure time in a test run.

IV. PRELIMINARY FINDINGS

The four materials which were exposed to weight loss damage tests have physical properties briefly summarized as follows:

> aluminum type 1100F annealed, ultimate strength 13,000 psi, Brin. hard 23
>
> cast iron "as cast"
>
> stainless steel type 430, annealed, ultimate strength 70,500 psi, Brin. hard 152
>
> Stainless steel type 304 cold drawn, annealed, ultimate strength 90,000 to 125,000 psi

A graphical summary of the weight loss tests on these four materials is shown in Fig. 5.

The general character of the damage inflicted on a test specimen is shown in photographs taken at the completion of a test series. Figure 6 shows for the aluminum alloy in part (a) the results at 500 fps. Part (b) shows the results for 750 fps and part (c) for 1000 fps. The photos demonstrate plastic flow with considerable uplift deformation at the edge of the impact region. Part (a) shows impact positioning fairly well confined whereas part (b) shows some wandering of impact around a deep central hole. Part (c) again shows a condition of some wandering about the deep central hole and additionally shows a large area of secondary erosion by spray following the initial impacting. Visual studies of the impacting droplet indicate that with a smooth surface the droplet spreads slightly radially on the target face and then rebounds in a spray which moves radially outward and away from the face. This spray evidently moves fast enough so that it clears the target sweep path without again striking the target. However, as shown in Fig. 6(c) the spray rebounding from a highly roughened surface moving at 1000 fps does make a second damaging impact.

The half hour impact tests on the type 430 stainless steel failed to show any weight loss with an impact velocity of 500 fps but yielded the data of Fig. 5 at 750 and 1000 fps. The photos of Fig. 7 show a very slight evidence of plastic deformation. It is noteworthy that the last points on the weight loss curve of Fig. 5 for a velocity of 1000 fps showed a punching through of the target specimen which was approximately 1/16 in. thick at the impact point. It is interesting to note that the diameter of the large outer end of this hole as shown in Fig. 7(b) is approximately the diameter of the impacting droplets (0.047 in.).

The impact tests on the type 304 stainless steel were run at 1000 and 1250 fps with weight loss results as shown in Fig. 5. Photographs of these specimens are not included but have a considerable resemblance to those of the 430 stainless steel shown in Fig. 7. The major difference between the 304 and 430 alloys in Fig. 5 is the substantial "incubation" or delay time before weight loss occurs with the 304 alloy.

Thiruvengadam and Preiser [16] outlined four zones of cavitation damage, based on vibratory tests, which also seem applicable to impact erosion damage. These zones which are evaluated in terms of weight loss per unit of time are described as:

> Zone 1. An incubation or no weight loss zone. In cavitation tests with a vibratory apparatus this was shown to depend on amplitude for a given frequency.
>
> Zone 2. Accumulation zone. A zone in which the energy absorption rate increases with time resulting in increasing loss of material with increasing test duration.
>
> Zone 3. Attenuation zone. The rate of weight loss reaches a peak value and begins to decrease. This zone is reported to be characterized by the formation of isolated deep craters on the surface of the test material indicating that the attenuation of energy absorption is associated with the influence of the craters on the bubble collapse process.
>
> Zone 4. Steady state zone. The rate of weight loss reaches a constant value.

These four zones are not directly identified in the accumulated weight loss type of plotting used in Fig. 5 but can be distinguished in an alternate plotting using weight loss per unit time. An alternate plot of this type for data relating to the 304 and 430 stainless steel is shown in Fig. 8. The plotting of Fig. 8 serves to show the same general form as weight loss data from other types of facilities as summarized by Thiruvengadam and Preiser [16]. However, despite this similarity there is reason to question their use of zone 4 damage rates as the most useful index of a material's resistance. Actually, only the time or rate values of zone 1 and zone 2 are directly associated with the material characteristics whereas the values of zones 3 and 4 additionally involve the overriding influence of the progressive cratering. Since the local cratering environment differs for each type of test facility and for every prototype application, there is little reason to believe that zone 4 evaluations will be meaningful in an absolute sense. In consequence this suggests that future impact damage or cavitation damage tests should give prime emphasis to damage values relating to zones 1 and 2.

There is some indication in the limited test data of Fig. 5 that meaningful damage evaluations can be derived from zone 1 for an impact type of facility. This is based on the fact that the facility can produce controlled impact conditions which are subject to a fairly rational analysis of the resulting loading and that controlled numbers of load cycling can be applied. In short, this concept is one of fatigue failure in which some combination of stress value and cycles of application determines the failure.

This concept is given some substance if the data of Fig. 5 for the 304 stainless steel are converted to values of stress and cycles of stress. The cycles of stress to failure may be evaluated by assuming that failure occurs where the horizontal line representing zone 1 intersects the sloping line representing zone 2. For the 304 stainless with an impact velocity of 1000 fps the intercept occurs at a time equivalent to 8.6×10^4 cycles and for a velocity of 1250 fps at 1.7×10^4 cycles.

The value of the peak impact pressure stress may be roughly approximated by the expression $p = \alpha\rho c v$ employed many years ago by Ackeret and deHaller and given more recent consideration by Engels [17]. In this expression α is an arbitrary constant which approximates and is assumed to be unity, ρ is the water density or 1.94, c is the acoustic velocity which is assumed as 4800 fps, and v is the relative velocity of impact. With this the v value of 1000 fps yields $p = 32 \times 10^3$ psi and the v value of 1250 fps yields $p = 40 \times 10^3$ psi. The equivalent value for the no damage test which was run at $v = 750$ fps yields $p = 24.2 \times 10^3$ psi.

The foregoing stress-cycles values are plotted in Fig. 9 together with longitudinal fatigue failure test values for an annealed 304 stainless steel as given in Ref. [18]. The relative agreement of these different types of test data may perhaps be fortuitous but is nevertheless encouraging in a preliminary experiment.

V. CONCLUSIONS

The equipment developed under this contract has shown a capability of eroding many typical structural materials by impact of a small liquid drop. It has the capability of repetitive impact on a small area of sample material under precise control of droplet mass and velocity.

The pattern of weight loss damage in tests with the impact facility shows a distinct similarity to weight loss values obtained from cavitation type test facilities.

Limited tests with ductile materials show marked deformation prior to loss of weight. More detailed tests with this apparatus can serve to more clearly define the transition from plastic flow to actual loss of material and the extent to which plastic flow may occur in the "incubation" period of harder materials.

The "incubation" period as defined earlier in this report and as evidenced in the tests with a self-hardening material has been shown to be a region capable of refined study with this type of apparatus. This is a particularly important region, for it serves to define the conditions under which a desirable type of material may be expected to fail. Preliminary findings indicate that failure represented by the limit of "incubation" may be rather directly associated with the better known fatigue failure properties of the material.

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F I G U R E S

(1 through 9)

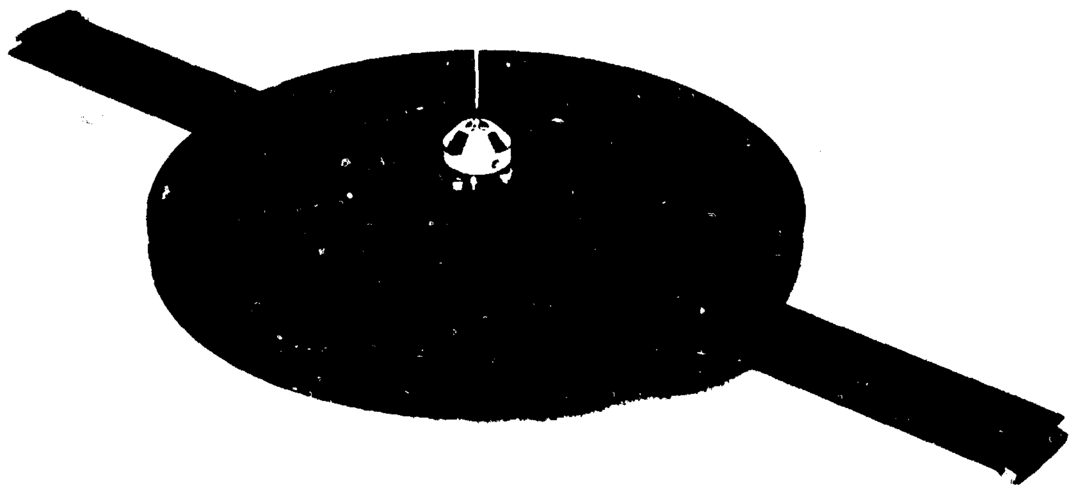


Fig. 1 - The Rotor Assembly

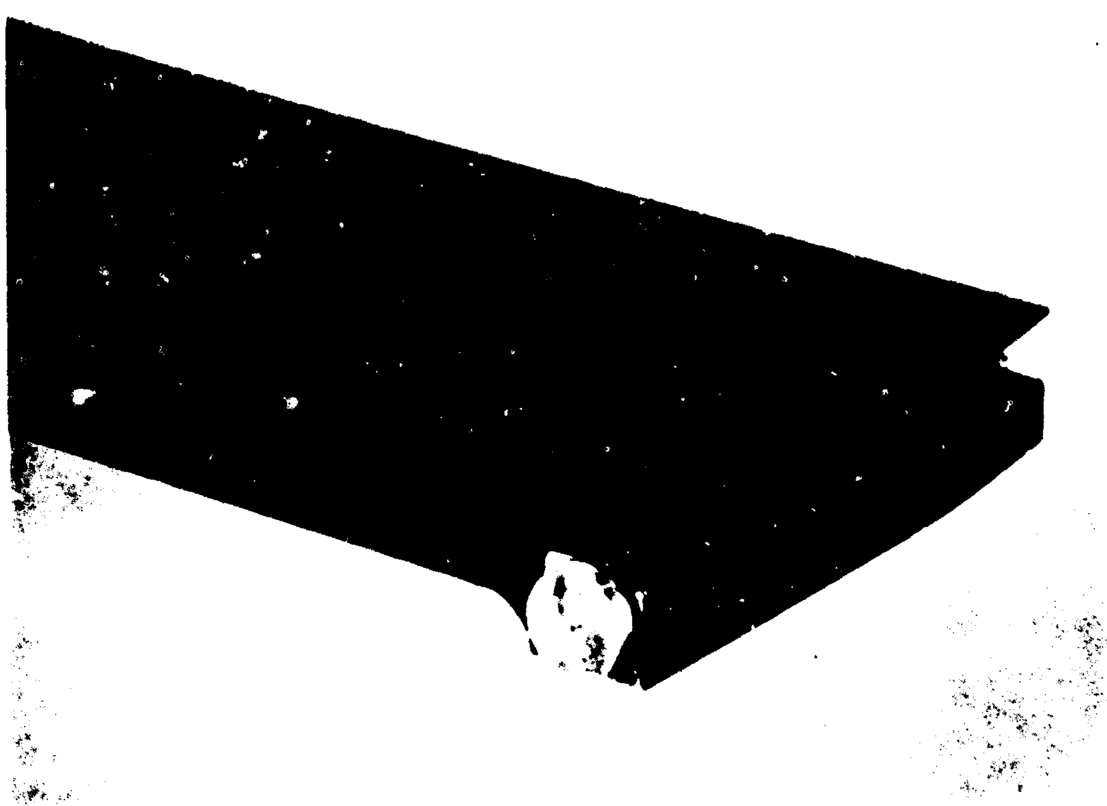


Fig. 2 - A Mounted Test Specimen at the Rotor Tip

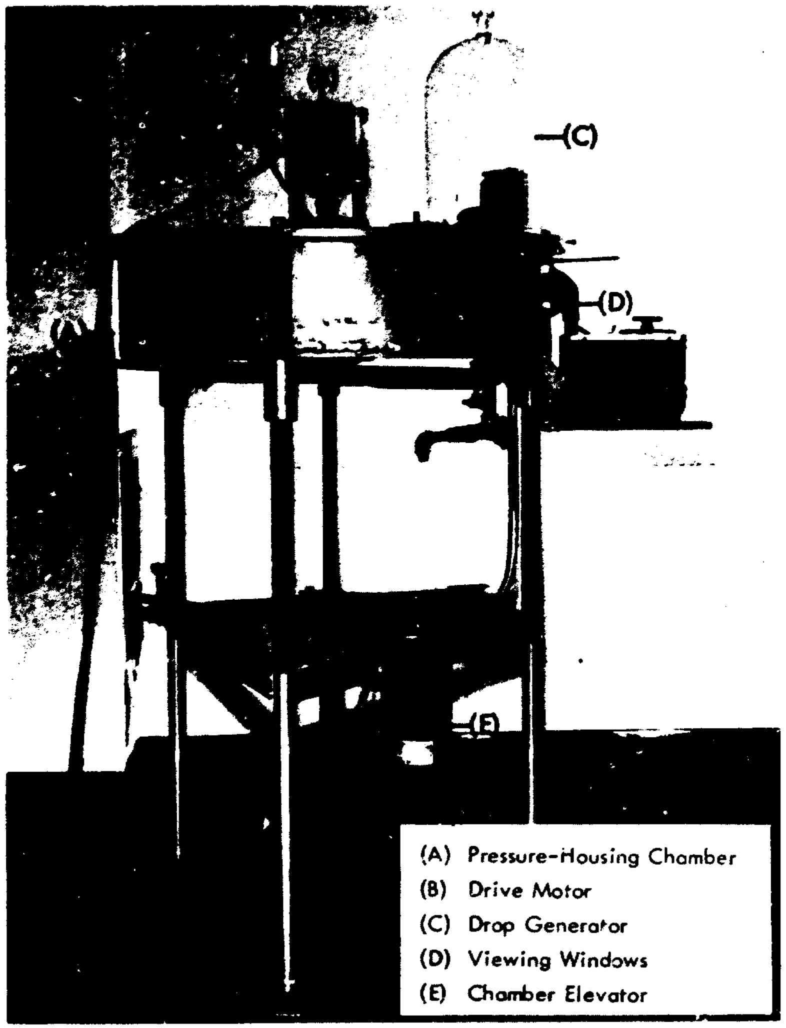


Fig. 3 - The Impact Damage Facility - Housing Chamber Closed

Fig. 4 - The Impact Damage Facility - Housing Chamber Open

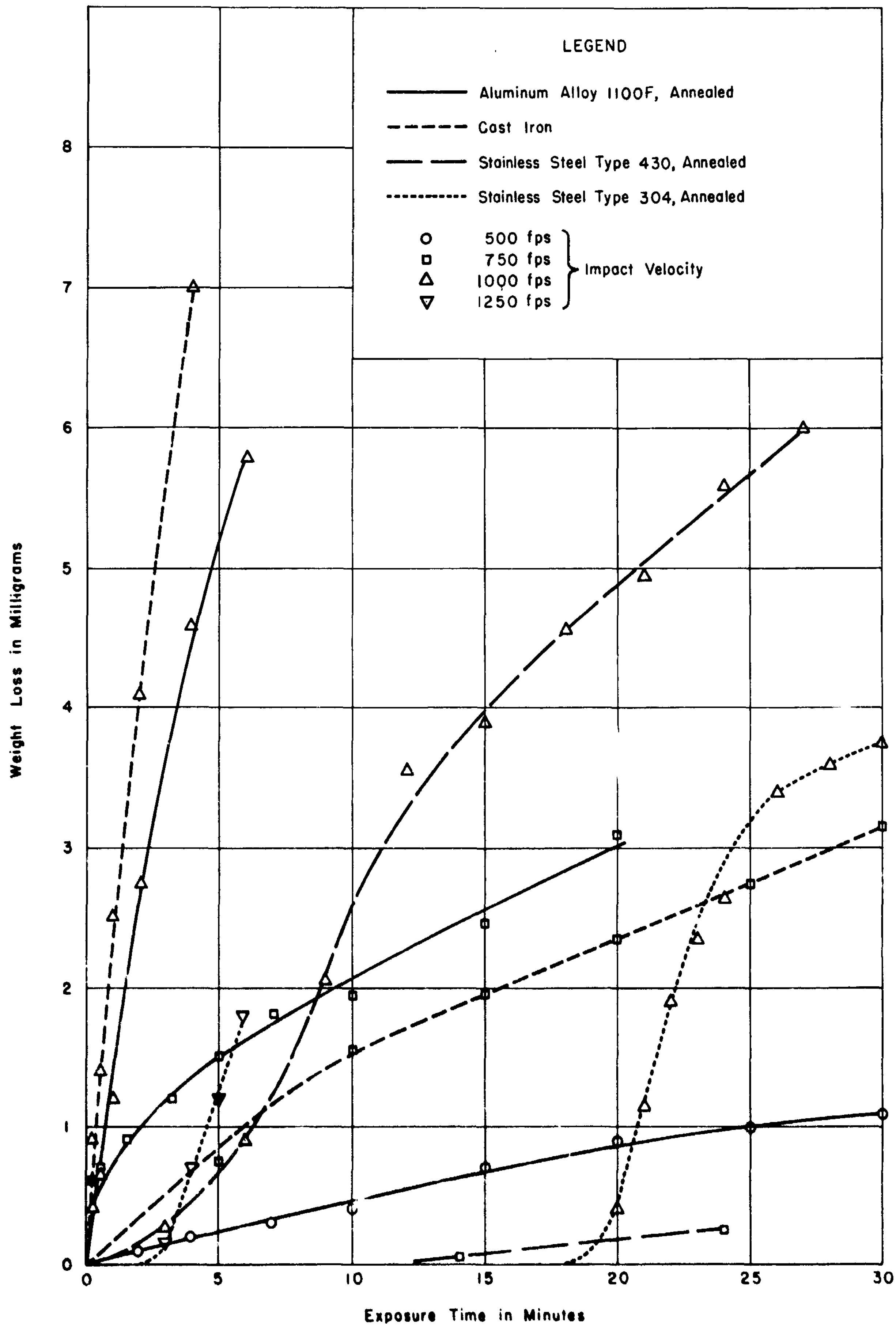


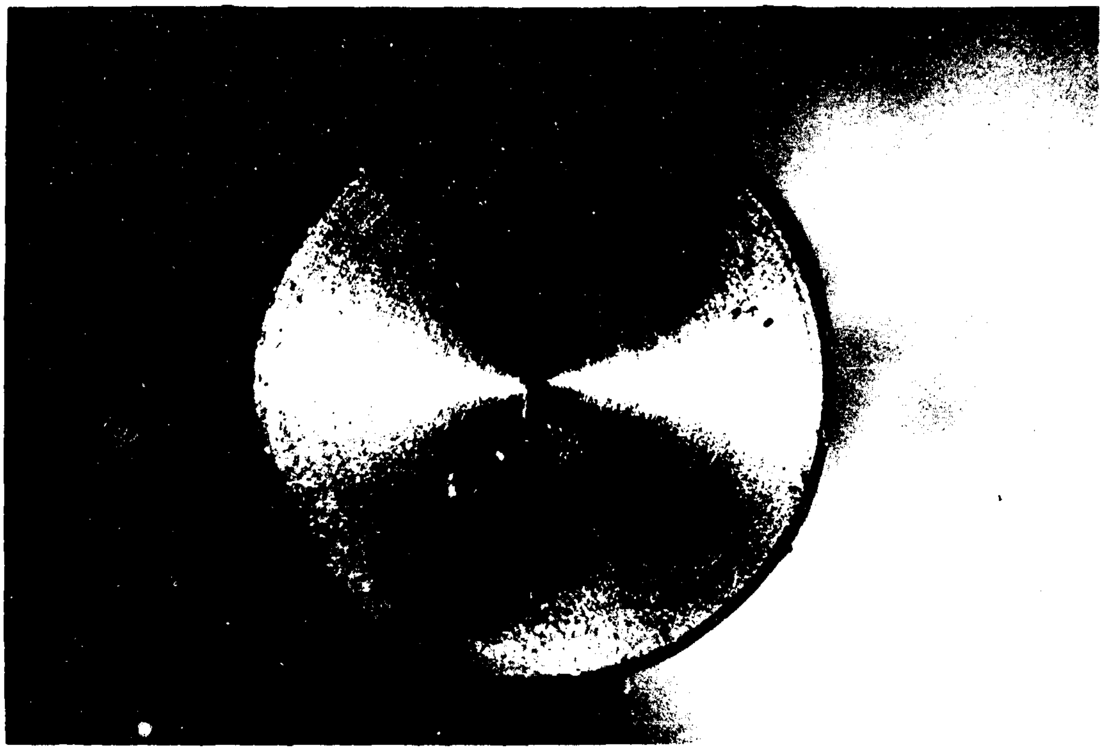
Fig. 5 - Weight Loss Damage for Various Materials and Exposures

(a) Velocity = 500 fps, Time = 30 min

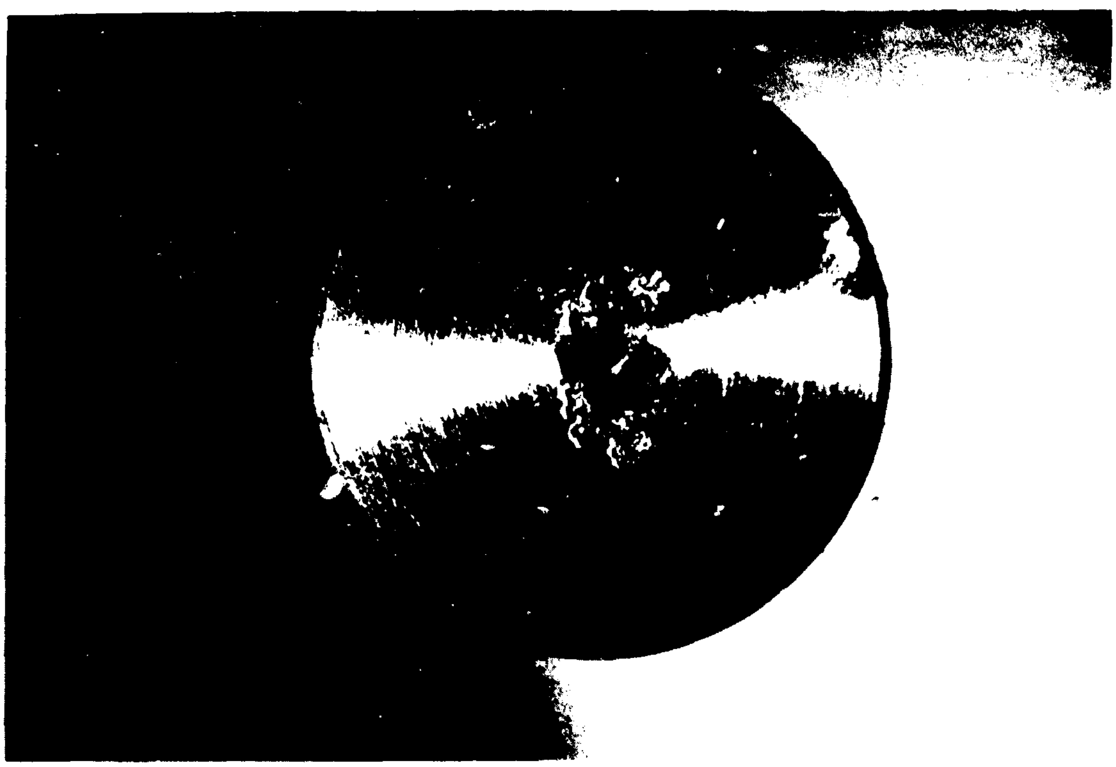
(b) Velocity = 750 fps, Time = 20 min

(c) Velocity = 1000 fps, Time = 6 min

Fig. 6 - Impact Damage, Aluminum Alloy 1100 F Annealed



(a) Velocity = 750 fps, Exposure Time = 24 min



(b) Velocity = 1000 fps, Exposure Time = 27 min

Fig. 7 - Impact Damage, Stainless Steel Type 430 Annealed

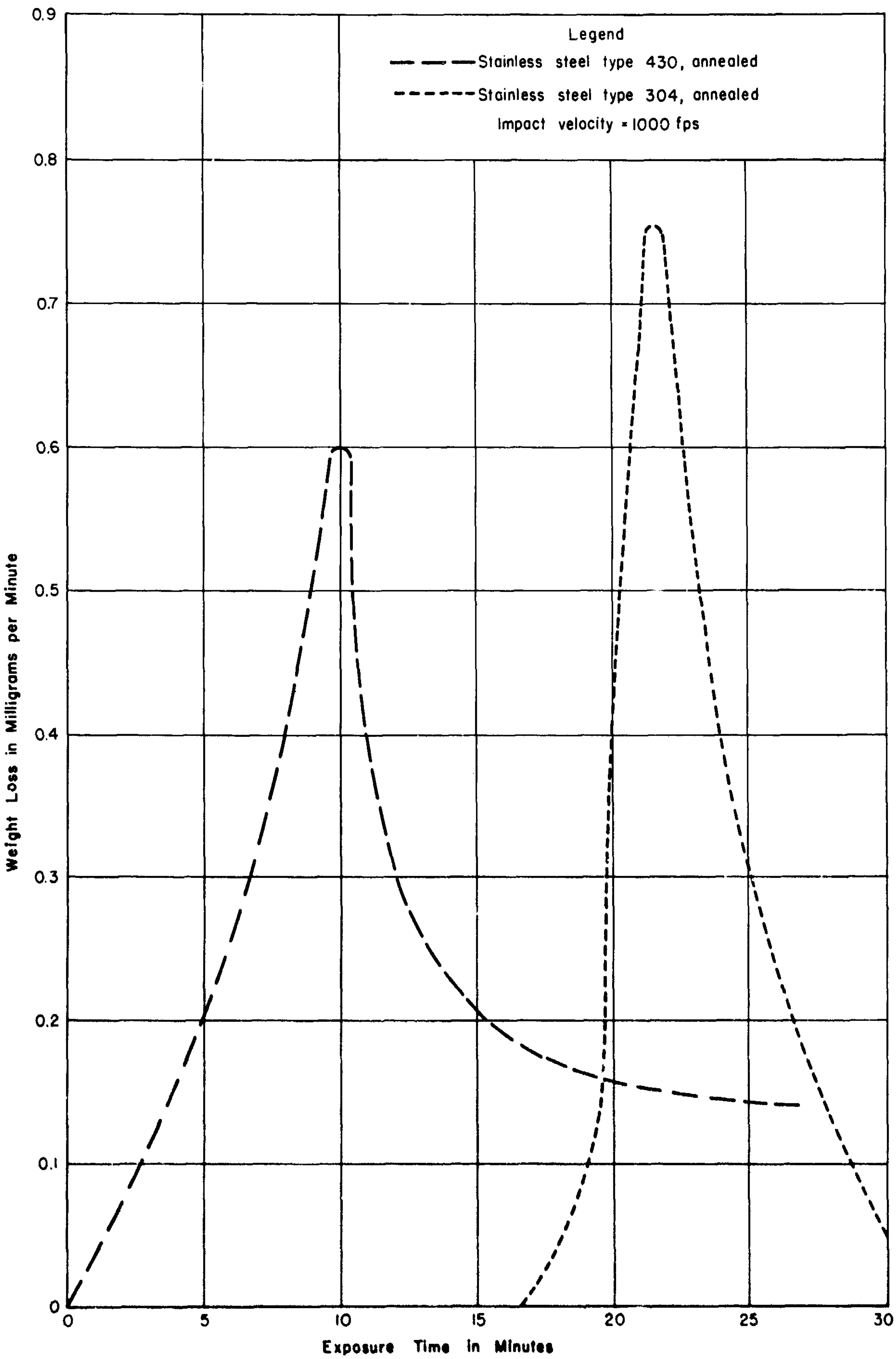


Fig. 8 - Damage Rate Values for Stainless Steel Types 304 and 430 Annealed

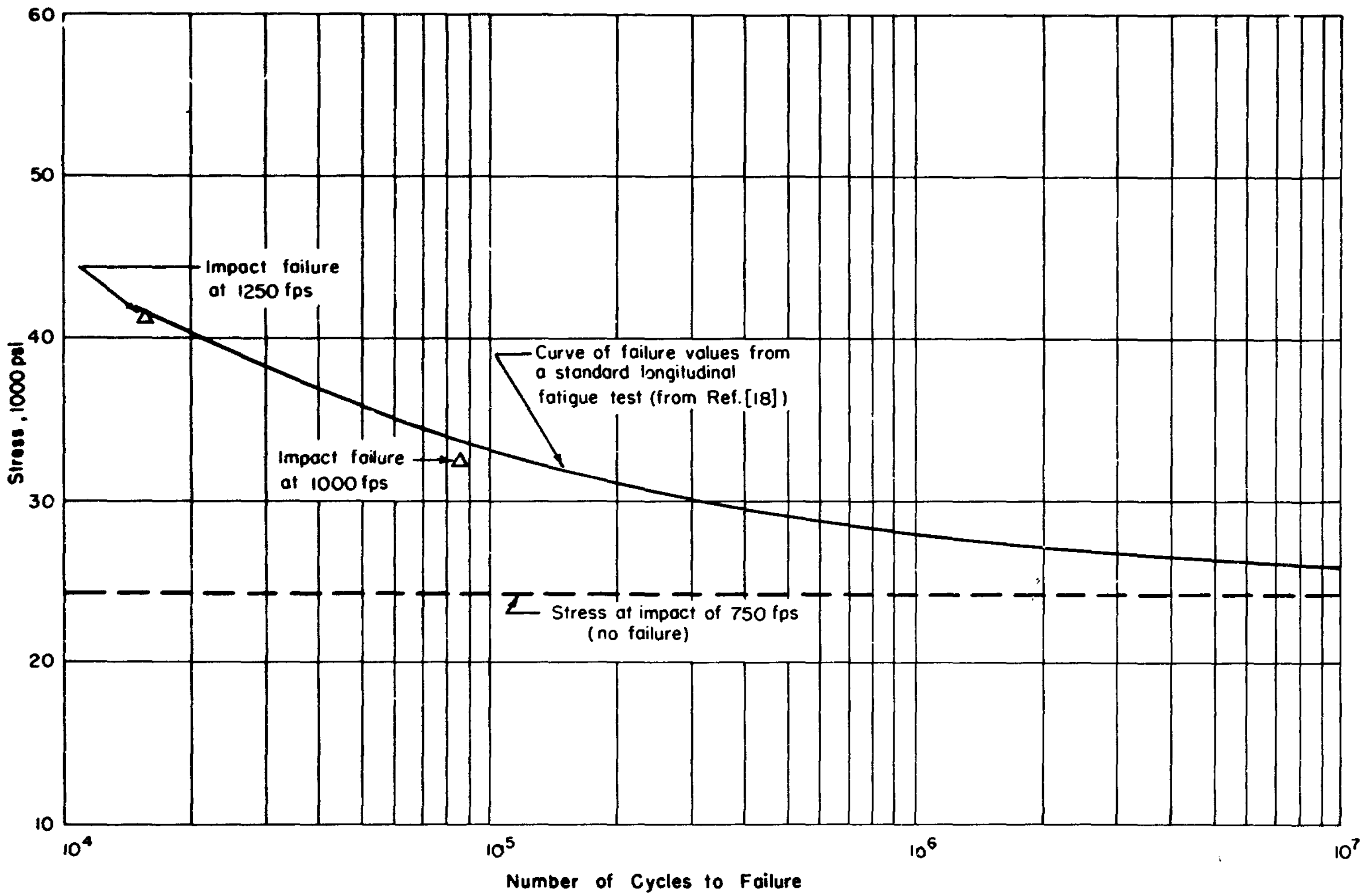


Fig. 9 - A Comparison of Impact Failure with Failure by a Standard Fatigue Method for 304 Stainless Steel

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A NEW FACILITY FOR EVALUATION OF MATERIALS SUBJECT TO EROSION AND CAVITATION DAMAGE, by John F. Ripken, John M. Killen, Scott D. Crist, and Roy M. Kuha. March 1965. 23 pages incl. 9 illus. Contract Nonr 710(56).

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1. Cavitation Damage
2. Impact Damage
3. Erosion
4. Material Evaluation

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