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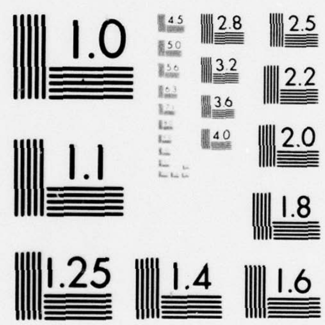

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RECENT PROGRESS IN UNDERSTANDING ENVIRONMENT ASSISTED FATIGUE CRACK GROWTH

by

R. P. Wei

G. W. Simmons

January, 1979

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Recent fracture mechanics and surface chemistry based studies have contributed to further understanding of environment assisted fatigue crack growth in high-strength alloys. The rate of fatigue crack growth in an aggressive environment, $(da/dN)_e$, may be considered to be the sum of three components.

$$(da/dN)_e = (da/dN)_r + (da/dN)_{cf} + (da/dN)_{scc}$$

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$(da/dN)_r$ is the rate of fatigue crack growth in an inert environment, and, therefore, represents the contribution of "pure" fatigue. $(da/dN)_{cf}$ represents a cycle-dependent contribution requiring synergistic interaction of fatigue and environmental attack. $(da/dN)_{scc}$ is the contribution by sustained-load crack growth (i.e., stress corrosion cracking) at K levels above K_{Iscc}. The cycle-dependent term has been shown to arise from the reaction of the environment with fresh crack surfaces produced by fatigue, and is a function of the extent of reaction during one loading cycle. For highly reactive alloy-environment systems, cracking response may depend also on the rate of transport of the aggressive environment to the crack tip. For gaseous environments, a formal basis for estimating pressure and frequency dependence has been developed. The framework and approach are expected to be applicable to other aggressive environments (such as, aqueous environments), and should provide a basis for the development of appropriate material evaluation and life prediction procedures.

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RECENT PROGRESS IN UNDERSTANDING ENVIRONMENT ASSISTED
FATIGUE CRACK GROWTH

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INTRODUCTION

Metal fatigue has been well recognized as an important cause for failure of engineering structures. In most applications, fatigue damage results from the conjoint actions of the cyclically applied stress and external (chemical) environment, and is therefore a time dependent phenomenon. Understanding of this load-environment interaction in fatigue is essential to the formulation of rational life prediction procedures and to the development of realistic materials evaluation and qualification tests. Quantitative characterization and understanding, however, have been hampered by the complexity of the phenomenon, by difficulties in separating the effects associated with crack initiation from those associated with crack growth, and by the influence of external chemical environments on both the initiation and growth processes.

With the increased emphasis placed on fatigue crack growth in many applications since the early 1950's and the development of fracture mechanics technology, separate considerations of the processes associated with fatigue crack growth evolved more or less naturally. This separation has provided better definition and focus, and has been by and large beneficial in terms of developing understanding of environment assisted fatigue crack growth. In this paper, the background and recent progress in understanding environment assisted fatigue crack growth are described. Implications of current understanding in terms of service performance and life prediction procedures are considered.

BACKGROUND

Studies of the influence of environment on fatigue crack growth began in the mid 1960's and have continued throughout the past 15 years. The results from the various studies have been reviewed and summarized in a number of papers (Gallagher and Wei, 1972; McEvily and Wei, 1972; Wei, 1970) and in the proceedings of conferences (Fatigue Crack Propagation, 1967; Corrosion Fatigue, 1972). Most of the early studies were directed at characterizing fatigue crack growth response, and at examining the influences of different loading variables on environment assisted fatigue crack growth. Results from these early studies served to demonstrate the complexity of the problem, and showed that many of the observed effects of loading variables can be traced directly to their interactions with the environment (McEvily and Wei, 1972; Wei, 1970). It became apparent also that a better understanding of the underlying processes for environment assisted fatigue crack growth is needed to provide a rational basis for the interpretation of crack growth data. A number of issues began to crystallize by the early 1970's. These issues relate to the reported differences in response to frequency and waveform for aluminum alloys (Bradshaw and Wheeler, 1968; Hartman and coworkers, 1967; Hudak and Wei, 1972; Wei, 1968) and steels (Barsom, 1972; Gallagher, 1971; Wei, Talda and Li, 1967), the relationship between environment assisted sustained-load crack growth (stress corrosion cracking) and fatigue crack growth (corrosion fatigue) (Miller, Hudak and Wei, 1973, Speidel and coworkers, 1972; Wei and Landes, 1969), and the cause or mechanism for environment assisted fatigue crack growth below the so-called stress corrosion cracking threshold (K_{Iscc})[1] (Wei and Speidel, 1972; Wei and Simmons, 1977). The most important issue, insofar as it relates to phenomenological understanding of load-environment interactions, appears to be the identification of the rate controlling process for environment assisted crack growth (Simmons, Pao and Wei, 1978; Wei and Simmons, 1977). The possible sequential processes involved in environment assisted crack growth are illustrated schematically in Fig. 1, for example, for a ferrous alloy exposed to a hydrogenous gas (Wei, 1979). The need for and development of a fundamental approach for addressing these issues are discussed by Wei and Simmons (1977), Wei (1979) and Williams, Pao and Wei (1979).

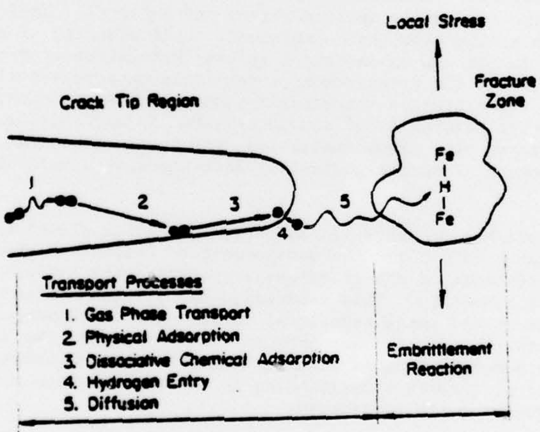

Fig. 1. Schematic illustration of various sequential processes involved in embrittlement by external gaseous environments. (Embrittlement reaction is depicted by the Fe-H-Fe bond.) (After Wei, 1979.)

Using an integrated interdisciplinary approach, Simmons, Pao and Wei (1978) sought to identify the rate controlling process for crack growth in water/water vapor for a high-strength (AISI 4340) steel. To this end, sustained-load crack growth experi-

[1] K_{Iscc} is the apparent threshold stress intensity (K) level for stress corrosion cracking and is defined as the asymptotic value of K as the rate of crack growth under sustained load approaches zero (Brown and Beachem, 1965; Wei, Novak and Williams, 1972).

ments were carried out in hydrogen and in water to determine the kinetics of crack growth as a function of temperature. Companion experiments were carried out on the same steel to determine the kinetics of water-metal surface reactions using Auger electron spectroscopy (AES). These studies were supplemented by detailed fundamental studies of reactions of water vapor with iron single crystals by AES and LEED (low energy electron diffraction) (Dwyer, Simmons and Wei, 1977), and by AES analysis of the elemental composition of fracture surfaces produced by environment assisted crack growth (Wei and Simmons, 1976). Through these coordinated interdisciplinary studies and comparisons of activation energies for crack growth and for surface reactions, the rate controlling process for crack growth was identified to be a slow step in the reaction of water/water vapor with iron and, perhaps, iron carbide (Dwyer, Simmons and Wei, 1977; Simmons, Pao and Wei, 1978). This reaction step is associated with the nucleation and growth of oxide on the surface, and the presumed concomitant production of hydrogen (Simmons, Pao and Wei, 1978).

Having identified the rate limiting process for sustained-load crack growth for this high-strength steel in water/water vapor, Pao, Wei and Wei (1979) examined its implication in terms of environment assisted fatigue crack growth response. Their results indicated that both steady-state and nonsteady-state crack growth response can be adequately explained in relation to the kinetics of surface reactions. Based on this success, the integrated interdisciplinary approach has been extended to the study of environment assisted fatigue crack growth response in an aluminum alloy (Wei and coworkers, 1979). This later study expands on an earlier suggestion by Bradshaw and Wheeler (1968) that the enhancement of fatigue crack growth in aluminum alloys by water vapor is determined by the exposure (pressure x time) during each load cycle. The results from these recent investigations are summarized and their engineering significance are considered.

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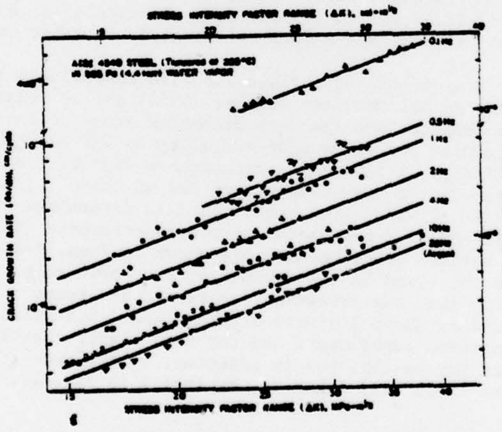

Fig. 2. Room temperature fatigue crack growth kinetics on AISI 4340 steel tested in dehumidified argon and in water vapor (below K_{Iscc}) at R = 0.1. (After Pao, Wei and Wei, 1979.)

RECENT PROGRESS IN UNDERSTANDING ENVIRONMENTAL EFFECT

Pao, Wei and Wei (1979) examined the effect of cyclic-load frequency (0.1 to 10 Hz) on fatigue crack growth in a high-strength (AISI 4340) steel tested in water vapor at room temperature. A water vapor pressure of 585 Pa was selected to preclude capillary condensation at the crack tip. Steady-state crack growth data from this study are shown in Fig. 2, and confirm the existence of a substantial effect of frequency at K_{max} levels well below that required for producing significant crack growth under sustained loads (that is, below K_{Iscc}) (Barsom, 1972; Gallagher, 1971). Fractographic data indicated that at the higher frequencies (namely, 10 Hz), the fracture surface morphology was akin to that for "pure" (mechanical) fatigue. At the lower frequencies (that is, below 1 Hz), on the other hand, the morphology exhibited increasing amounts of intergranular separation along prior-austenite grain boundaries that is typical for sustained-load crack growth in water/water vapor (Simmons, Pao and Wei, 1978). These observations, taken in conjunction with previous studies, suggested that the steady-state fatigue crack growth rate in an aggressive environment is composed of two components — one for "pure" fatigue and the other representing the environmental contribution. Because the rate controlling process has been identified to be a slow-step in the water-metal surface reaction in this case, the environmental component is expected to depend on the time available for this reaction (namely, the cyclic load period) and on the reaction kinetics. In other words, the extent of crack growth during one loading cycle is expected to be proportional to the extent of reaction (or surface coverage) during that cycle. Based on data on the kinetics of surface reactions (Simmons, Pao and Wei, 1978), the environment contribution[2] should vary almost linearly with the cyclic load period or inversely with frequency, over the range of frequencies used in their investigation, Figs. 3 and 4 (Pao, Wei and Wei, 1979). At high frequencies, environmental effect should be essentially negligible; at low frequencies, it should reach a maximum or a saturation value. This general trend is consistent with data reported by Gallagher (1971) for fatigue crack growth in a high-strength (HY-80) steel in 3.5 pct NaCl solution (Fig. 5), and by Bradshaw and Wheeler (1968) on an aluminum (DTD 5070A) alloy in water vapor.

To further verify the concept of surface reaction control and to follow up on the earlier suggestions by Bradshaw and Wheeler (1968) and by Hudak and Wei (1972), a combined surface chemistry and fracture mechanics study of fatigue crack growth in water vapor was carried out on an aluminum alloy by Wei and Simmons and their coworkers (1979). Fatigue crack growth experiments were carried out as a function of water vapor pressure at room temperature for an Al-Cu (2219-T851) alloy. The reactions of this alloy with water vapor was also determined by Auger electron spectroscopy (AES) and by x-ray photoelectron spectroscopy (XPS). The fatigue crack growth and surface reaction data are shown in Figs. 6-8. Comparison of Figs. 7 and 8 indicates the trend in the fatigue crack growth and surface reaction data are similar, except that the exposures (expressed as pressure x time or pressure/frequency) differed by about 3 orders of magnitude. Recognizing that at the low pressures used in these experiments and for this highly reactive system, the environmental effect may be limited, in addition, by the rate of transport of the environment to the crack tip[3] (that is, by step 1 in Fig. 1), an estimate of this

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[2] The environmental contribution is represented by the difference of two empirical constants, $C - C_o$, determined by least-squares fit to the data in Fig. 2 using $da/dN = C\Delta K^2$. This empirical relationship provided a convenient means for representing these data, but does not have general validity.

[3] Transport limitation has been suggested by the companion fractographic observations (Wei and coworkers, 1979).

influence has been made (Wei and coworkers, 1979). This estimate showed that by incorporating the transport process, good correlation between surface reaction kinetics and the rate of environment assisted fatigue crack growth in the aluminum alloy can be obtained (see Fig. 9).

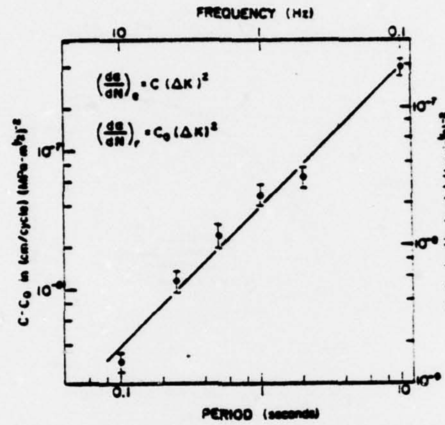

Fig. 3. Environment dependent component of fatigue crack growth parameter as a function of cyclic load period for AISI 4340 steel tested in water vapor at room temperature. (After Pao, Wei and Wei, 1979.)

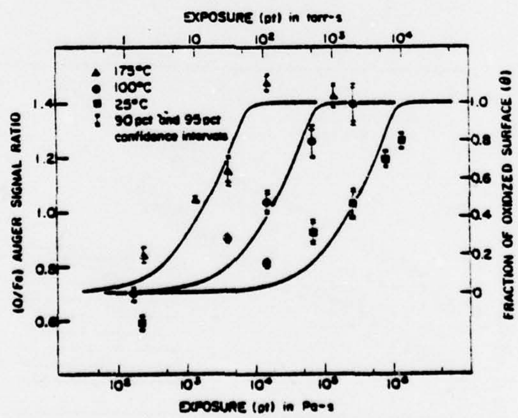

Fig. 4. Kinetics of reaction of AISI 4340 steel with water vapor at three temperatures. (The steel surface was ion etched prior to each exposure to water vapor.) (After Simmons, Pao and Wei, 1978.)

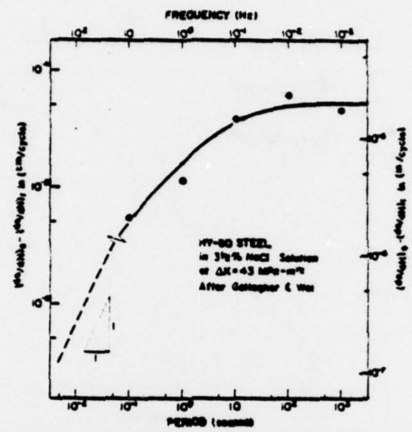

Fig. 5. Environment dependent component of fatigue crack growth rate as a function of cyclic load period for HY-80 steel tested in 3.5 pct NaCl solution at room temperature. (After Gallagher, 1971; Gallagher and Wei, 1972; Pao, Wei and Wei, 1979.)

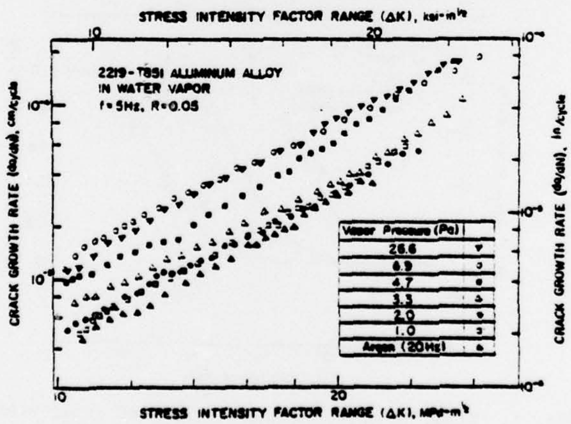

Fig. 6. Influence of water vapor pressure on the kinetics of fatigue crack growth in 2219-T851 aluminum alloy at room temperature. (After Wei and coworkers, 1979.)

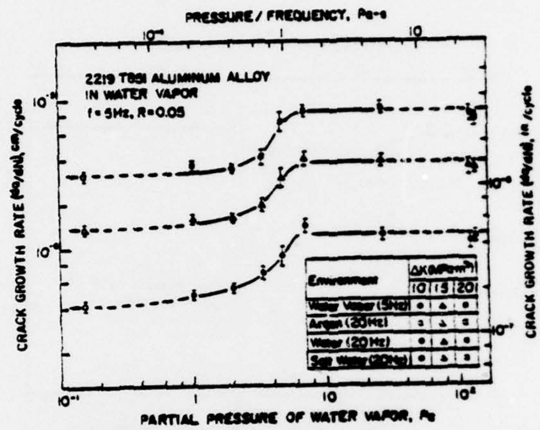

Fig. 7. Influence of water vapor pressure (or pressure/frequency) on fatigue crack growth rate in 2219-T851 aluminum alloy at room temperature. (After Wei and coworkers, 1979.)

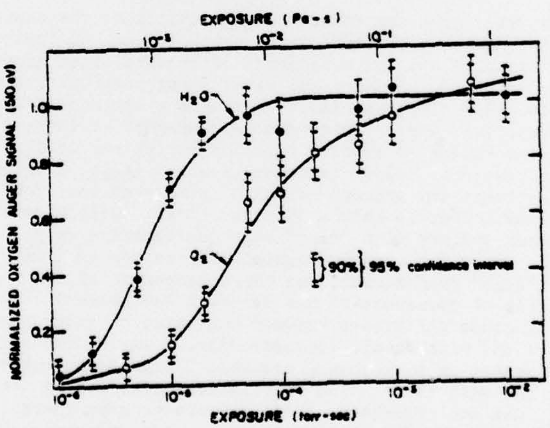

Fig. 8. Kinetics of reactions of 2219-T851 aluminum alloy with oxygen and with water vapor at room temperature. (After Wei and coworkers, 1979.)

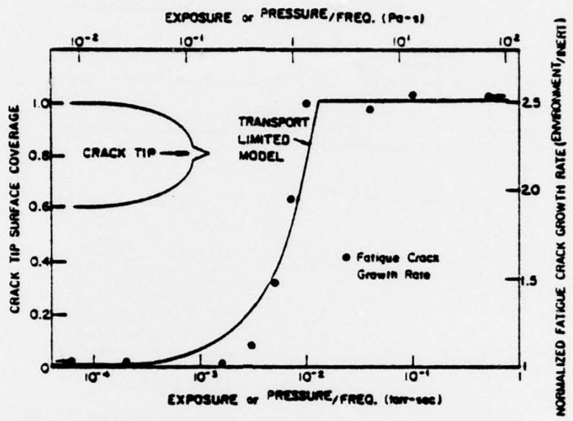

Fig. 9. **Comparison between the observed fatigue crack growth response, for 2219-T851 aluminum alloy tested in water vapor at room temperature, and preduction of a transport-limited model.** (After Wei and coworkers, 1979.)

These recent studies have contributed significantly to the phenomenological understanding of environment assisted fatigue crack growth. Correlation between the surface reaction kinetics and the dependence of fatigue crack growth response (below K_{Iscc}) as a function of frequency and water vapor pressure has now been established for these two very different alloy-environment systems. Two separate regimes can now be identified, where environment enhancement of fatigue crack growth is determined by the extent of surface reaction during one loading cycle. For alloy-environment systems with "slow" reaction kinetics (e.g., steel-water vapor system), environmental effects are evident at "high" pressures and "low" frequencies, and crack growth enhancement is only a function of the surface reaction kinetics. For alloy-environment systems with "fast" reaction kinetics (e.g., aluminum-water vapor system), on the other hand, environmental effects now manifest themselves at "low" pressures and "high" frequencies, and the enhancement of crack growth now also depends on the rate of transport of the external environment to the crack tip. The 8 orders of magnitude difference between the rates of water vapor reactions with aluminum alloys and with steels (compare Figs. 3 and 8) can readily account for the observed differences in environment assisted fatigue crack growth response for these alloys (Hudak and Wei, 1972). The correlation developed in these studies (Pao, Wei and Wei, 1978; Wei and coworkers, 1979) appears to have general applicability for the enhancement of fatigue crack growth in gaseous environments, and provides a basis for assessing environmental effects. Extension of the basic concept and approach to the consideration of cracking problems in aqueous environments should prove to be useful and is being explored.

MODELING AND ENGINEERING IMPLICATIONS

Based on the recently developed understanding and on research over the past 15 years, a rational basis for treating environment assisted fatigue crack growth has been suggested (Wei, 1979). The rate of fatigue crack growth in an aggressive environment, $(da/dN)_e$, is considered to be the sum of three components.

$$
\begin{aligned}
(da/dN)_e &= (da/dN)_r + (da/dN)_{cf} + (da/dN)_{scc} \\
&= (da/dN)_r + (da/dN)_{cf} + \int_0^{\tau} [da/dt(K)]\, dt
\end{aligned}
$$

$(da/dN)_r$ is the rate of fatigue crack growth in an inert environment and, therefore, represents the contribution of "pure" (mechanical) fatigue. This component is essentially independent of frequency at temperatures where creep is not important. $(da/dN)_{cf}$ represents a cycle-dependent contribution requiring synergistic interaction of fatigue and environmental attack. $(da/dN)_{scc}$ is the contribution by sustained-load crack growth (that is, stress corrosion cracking) at K levels above K_{Iscc} (Wei and Landes, 1969).

Detailed examinations of the contribution by sustained-load crack growth, that is the $(da/dN)_{scc}$ term, have been made previously (Miller, Hudak and Wei, 1973; Wei and Landes, 1969). For usual engineering applications, however, alloys that are highly susceptible to sustained-load crack growth (stress corrosion cracking) would not be used, and the $(da/dN)_{scc}$ term is primarily of academic interest. The cycle-dependent term, $(da/dN)_{cf}$, on the other hand, is quite important. Its existence has been recognized by researchers for some time (Barsom, 1972; Gallagher, 1971; Parkins and Greenwell, 1977; Speidel and coworkers, 1972; Wei, 1970). A formal framework for estimating the frequency and pressure dependence in gaseous environments is beginning to emerge.

The cycle-dependent term, however, has not been fully appreciated by most of the engineering community. Its impact must be recognized and taken into account in the development of design data, and particularly in the use of the so-called accelerated tests. By the same token, reliability of service life predictions depend on a proper accounting of the environmentally induced effects.

SUMMARY

Recent fracture mechanics and surface chemistry based studies have contributed to further understanding of environment assisted fatigue crack growth in high-strength alloys. The rate of fatigue crack growth in an aggressive environment, $(da/dN)_e$, may be considered to be the sum of three components.

$$(da/dN)_e = (da/dN)_r + (da/dN)_{cf} + (da/dN)_{scc}$$

$(da/dN)_r$ is the rate of fatigue crack growth in an inert environment, and, therefore, represents the contribution of "pure" fatigue. $(da/dN)_{cf}$ represents a cycle-dependent contribution requiring synergistic interaction of fatigue and environmental attack. $(da/dN)_{scc}$ is the contribution by sustained-load crack growth (i.e., stress corrosion cracking) at K levels above K_{Iscc}. The cycle-dependent term has been shown to arise from the reaction of the environment with fresh crack surfaces produced by fatigue, and is a function of the extent of reaction during one loading cycle. For highly reactive alloy-environment systems, cracking response may depend also on the rate of transport of the aggressive environment to the crack tip. For gaseous environments, a formal basis for estimating pressure and frequency dependence has been developed. The framework and approach are expected to be

applicable to other aggressive environments (such as, aqueous environments), and should provide a basis for the development of appropriate material evaluation and life prediction procedures.

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