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Boron Carbide Combustion in Solid-Fuel Ramjets Using Bypass Air. Part I: Experimental Investigation

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Borcarbid-Abbrand in Feststoff-Staustrahltriebwerken unter Verwendung eines Luftnebenstroms. Teil I: Experimentelle Untersuchung

Die Wirkung eines Luftnebenstroms (Bypass-Air) auf den Abbrand von hochgefüllten Borcarbid/HTPB-Treibsätzen in einem Feststoff-Staustrahltriebwerk wurde experimentell untersucht. Es wurde gefunden, daß der Abbrand-Wirkungsgrad beträchtlich zunimmt bei Anwendung hoher Bypass-Verhältnisse mit niedrigem Strömungsimpuls. Die Ergebnisse zeigten, daß bei hohem Strömungsimpuls die Brennstoffpartikel mit der Kammerwand kollidieren und ausgelöscht werden. Zunahme des Druckes erhöht den Wirkungsgrad, anscheinend durch die daraus resultierende längere Verweilzeit. Ein erhöhtes Gesamt-Äquivalenzverhältnis (Treibsatzlänge) erwies sich ebenfalls als nützlich, da es einen geringeren Anteil an größeren Partikeln in der Umlaufzone erzeugt. Eine gewisse Verringerung des Abbrandwirkungsgrades war eher die Folge einer unvollständigen Verbrennung des HTPB als der Borcarbid-Partikel.

Combustion de carbure de bore dans des stato-réacteurs à propergol solide en utilisant un flux d'air de dilution. 1ère partie: étude expérimentale

On a étudié expérimentalement l'effet d'un flux d'air de dilution sur la combustion d'un bloc de poudre carbure de bore/HTPB hautement chargé dans un statoréacteur à propergol solide. On a trouvé que l'efficacité de la combustion augmentait considérablement en utilisant des taux de flux de dilution élevés avec de faibles impulsions d'écoulement. Les résultats ont montré qu'avec des impulsions d'écoulement élevées, les particules de combustible heurtaient la paroi de la chambre et s'étaignaient. Une augmentation de la pression augmente le rendement, vraisemblablement du fait du temps de séjour plus long qui en résulte. L'augmentation du rapport d'équivalence global (longueur des grains) s'est également avérée utile, étant donné qu'il en résulte une réduction de la proportion de particules plus grandes dans la zone de recirculation. La réduction du rendement de combustion a été en partie due à une combustion incomplète du HTPB plutôt que des particules de bore.

Summary

The effects of bypass air on the combustion of highly loaded boron carbide/HTPB fuel grains in a solid-fuel ramjet motor were investigated experimentally. It was found that combustion efficiency can be significantly increased by employing high bypass rations with low dump momentum. The results indicated that high bypass dump momentum causes the particles to collide with the wall and extinguish. Increasing pressure increased efficiency, apparently through the resulting increased residence time. Increased overall equivalence ratio (grain length) also was found to be beneficial, the result of a smaller percentage of larger particles which are generated in the recirculation zone. Some of the reduction in combustion efficiency was determined to be due to incomplete combustion of the HTPB rather than just to the incomplete burning of the boron carbide particles.

1. Introduction

The solid-fuel ramjet (SFRJ) offers high specific impulse together with design simplicity. The addition of metals to the commonly used hydrocarbon (HC) fuels can provide a better energetic performance, especially for volume limited systems. Boron (B) exhibits remarkable theoretical energetic performance with the highest energy density of all elements, about three times that of HC fuels[1,2]. Boron carbide (B_4C) is capable of providing almost the same energy as boron; moreover, its commercial price is considerably lower. The realization of this theoretical energy in the motor environment is not straightforward. The difficulty in burning boron in the SFRJ environment was noted early in its development[3]. It is difficult to ignite the boron particles due to a molten oxide layer which is formed around the particle and serves as a barrier between the ambient oxygen and the boron. When the particle is heated enough, by convection and radiation, the oxide starts to evaporate and its thickness is reduced. The evaporation process is endothermic and this cools the particle. The particle ignites when and if the oxide layer is removed[4,5].

Though the ignition and combustion of boron particles in oxidizing, temperature-controlled atmospheres have been the subject of numerous studies[4–7], there have been only a few publications[8–14] that provide information on the behaviour of boron or boron carbide particles inside an SFRJ motor.

The use of boron in a SRFJ can be accomplished by introducing boron or boron carbide particles into a polymeric matrix. These particles tend to accumulate and agglomerate at the condensed fuel surface layer prior to their ejection into the gas flow. They may also be ejected from the fuel surface in thin flakes consisting of both particles and the binder[9]. After their ejection from the surface they move into a flowfield of nonuniform velocity, composition and temperature. The ignition and combustion characteris-

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tics of a particle are very much affected by the heat, mass and momentum transfer along its trajectory. Natan and Gany[11] showed that the requirements for ignition of individual boron particles may oppose the conditions necessary to sustain combustion of the particles. There is only a narrow regime in which both the requirements for ignition and combustion can coexist in the flowfield of the SFRJ combustor. Particles whose trajectories allow them sufficient residence time in the hot gas-phase diffusion flame zone within the boundary layer, ignite fairly readily (Fig. 1). However, even long residence times in this area do not permit high particle combustion rates due to the low oxygen content. On the other hand, particles whose high ejection velocities bring them rapidly into the oxygen rich region, above the flame zone, may not ignite at all due to their short residence time in the hot environment. The theoretical analysis of Natan and Gany[11] reveals that only small particles (less than 30 μm), and only when they leave the fuel surface at a very limited range of ejection velocities, may burn completely within an 1-m-long SFRJ combustor. The result is that the total fraction of boron that can burn within the combustion chamber is very small. If already-ignited particles reach an oxygen rich environment, they can burn at relatively high burning rates.

In recent years there has been some success in improving the combustion efficiency of boron/boron-carbide fueled grains by using additives to the fuel grain that probably enhance the heat release near the surface[9,10]. This kind of preheating of the particles can result in rapid removal of the oxide layer, and many of the particles can be ejected into the flow when they are already ignited. In fact, some of the earliest SFRJ investigations[2] utilized oxidizers within the fuel grain to enhance combustion, to the point that no sudden enlargement flameholder was required. The oxidizers were also used to provide burning rate control. With the oxidizers present a much shorter residence time is required for the ignition and the combustion processes, and the combustion efficiency of the fuel increases significantly. However, this enhanced combustion technique results in decreased specific impulse.

The use of an aft-burner where bypass air is added to the main flow (Fig. 2) has a number of beneficial effects:

(1) It promotes the ignition of the boron particles because of the lower air mass flux through the main combustor, which produces a thicker and hotter flame zone[15] and increases the residence time of the particle.
(2) It enhances the combustion of the already ignited particles due to better mixing of the particles with the air in the mixing chamber.
(3) It permits some control of the solid fuel regression rate and the overall fuel-to-air ratio as a result of the effect of the fuel-port air mass flux on the fuel regression rate.
(4) It permits increased fuel volumetric loading fraction which can increase range.

The ability to enhance the combustion efficiencies of metallized fuels in SFRJs was recognized early[2,3]. These early developments used as much as 90% bypass air together with devices to enhance mixing between the bypass

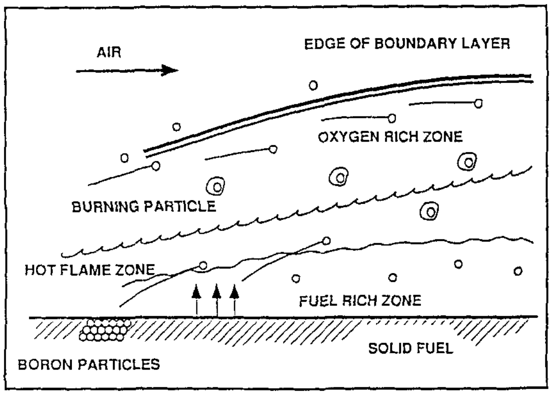

Figure 1. Metallized SFRJ combustion regime.

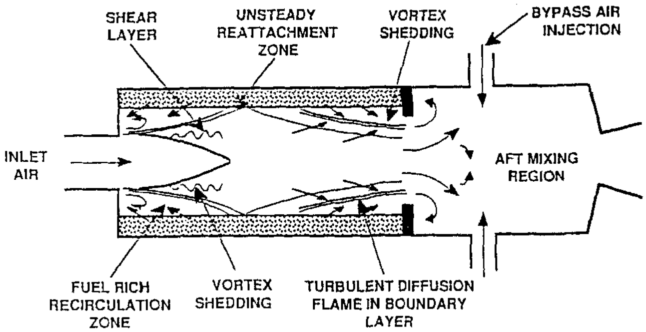

Figure 2. Schematic of a solid-fuel ramjet motor.

air and the fuel-rich products which exit from the fuel grain. More recently, the effects of bypass air on the boron combustion in SFRJ's has been investigated theoretically by Natan and Gany[12,13] and experimentally by Natan and Netzer[14]. These investigations demonstrated that bypass air can significantly improve the boron combustion efficiency. The experimental investigation[14] presented only very limited data, and it was not clear whether the bypass ratio and/or bypass air dump momentum had the dominant influence on the observed improvement in combustion efficiency.

The objective of the present research was to experimentally determine the effects of bypass ratio, bypass air dump momentum, combustion pressure, and equivalence ratio on the combustion efficiency of solid-fuel ramjets which utilize boron carbide fuel in bypass combustor geometries. In an attempt to better understand the effects of the test variables on the particulate combustion, particle-size distributions were measured at the nozzle entrance during some of the tests using a Malvern 2600 HSD particle sizer.

2. Experimental Apparatus and Procedure

The solid fuel ramjet tests were conducted at the Combustion Laboratory of the Department of Aeronautics and Astronautics, Naval Postgraduate School (NPS).

2.1 The Test Motor and Instrumentation

A sub-scale, 64 mm-diameter, coaxial dump, axisymmetric combustor configuration (Fig. 3) was utilized in the

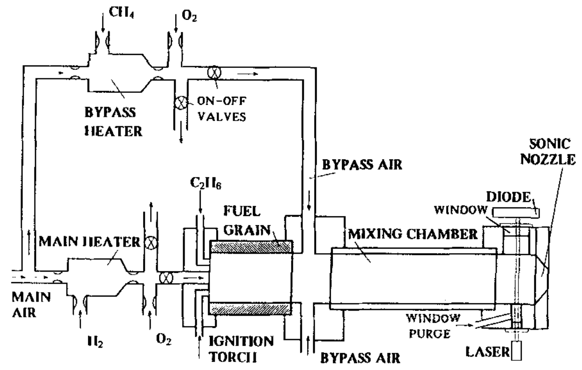

Figure 3. Experimental system.

direct-connect mode. The fuel grain was bolted between the inlet and the aft mixing chamber. Main air flowed through the grain while bypass air was introduced between the back end of the grain and the mixing chamber, through two 180°-opposed, 15 mm-diameter, dumps. In order to reduce heat loss through the combustor wall the mixing chamber was insulated with DC93–104, a Dow Corning ablative material with good high temperature characteristics. A sonic nozzle with graphite insert was bolted onto the aft mixing chamber.

Air flowed from high pressure (20 MPa) storage tanks through a pressure regulator and choked nozzles to two air heaters for the main and bypass air. Hydrogen and methane were used as fuels for the main and bypass air heaters respectively, while oxygen was injected downstream of the heaters to ensure that the vitiated air contained 23% oxygen by mass. Both air heaters were acoustically isolated from the ramjet combustor with sonically choked orifices.

The bypass air heater was ignited and the hot air was passed through the mixing chamber until the bypass inlet air temperature had stabilized. During this time, cold air was passed through the main combustion chamber to prevent heating of the fuel grain. Then the main heater was ignited and dumped to the atmosphere until the heater temperature had stabilized. At this time both main and bypass air were switched to the motor, initiating a computer controlled sequence of events in which the fuel grain was preheated for 4 seconds, the ramjet combustor was ignited and sustained for a burn time of 8 seconds, and finally quenched at the end of the test. The air heaters were aborted immediately after the burn ended. An ethylene/oxygen torch ignited the ignition gas (ethylene, injected into the recirculation zone), which in turn ignited the ramjet fuel grain. A 1.5 seconds ignition time was required for good ignition. Argon was used to quench the fuel.

A B_4C/Mg/HTPB (highly loaded, 50%, 5% and 45%, respectively) fuel grain was used for most of the tests. Additional tests were conducted with a fuel containing 55% B_4C and 45% HTPB. The fuel grains were supplied by the Naval Air Warfare Center Weapons Division, China Lake, CA.

Instrumentation for determining combustor performance consisted of combustor static pressures, main and bypass inlet air temperatures, and flow rates measurements.

2.2 Particle Size Distribution Measurement

Particle-size measurements were taken with a Malvern particle sizer, model 2600 HSD. The Malvern 2600 measurement is based on far-field, near-forward Fraunhofer light diffraction and had a measurement range of 1.9 μm–188 μm when using a 100-mm focal length Fourier transform lens. It also provides an estimate for the mass of particles with diameters between 0.5 μm and 1.9 μm. When non-spherical particles are present (such as the surface flakes reported leaving the fuel surface in the recirculation region at the head-end of the grain[9]) the measured result is the "volume equivalent" spherical diameter, which generally is between the minimum and maximum dimensions of the particle. An IBM/AT computer was used as the controller and triggered the Malvern to take readings at the appropriate time.

The laser beam passed through two fused-silica windows, one opposite to the other, which were held in place by retainers. The windows were kept clean during the combustion test by flowing air through a sintered bronze tube, keeping the window chambers free of combustion products. Approximately 8% of the total air mass flow was required as purge gas. The openings at each side of the test section were only large enough for the beam and scattered light to pass through.

2.3 Experimental Procedure

The test matrix was established to separate, as much as possible, the effects of each of the test variables on the combustion efficiency. The effects of chamber pressure were especially difficult to separate since improved combustion efficiency obtained from variation of another test variable also results in increased pressure. The tests were divided into five series (Table 1). "Primary" variables were deliberately varied with a greater than 40% change over the test series. "Secondary" variables varied 25%–30% over a given series and "approximately constant" parameters varied less than 12%.

Table 1. Test Matrix

Series	Primary Variables	Secondary Variables	Approximately Constant	Test No.
A	B_R, G_a, L_G	M_R, P_c	A_{th}, $\dot{m}_a$, T_i, Φ_0	1[a][b], 2, 3, 4[a]
B	L_G, φ_0	P_c	A_{th}, B_R, M_R, G_a, $\dot{m}_a$, T_i	5, 6, 7[a], 8, 9
C	M_R	(G_a, $\dot{m}_a$)	(G, $\dot{m}_a$), A_{th}, B_R, L_G, P_c, T_i, Φ_0	2, 10, 11[a]
D	M_R	P_c	A_{th}, B_R, G_a, L_G, $\dot{m}_a$, T_i, Φ_0	3, 7, 8, 12, 13, 14
E	A_{th}, P_c	φ_0	B_R, M_R, G_a, $\dot{m}_a$, L_G, T_i	15–20[b][c]

[a] Data from Ref. 14.
[b] No bypass air ($B_R = 0$).
[c] Fuel composition contained no Mg.

3. Experimental Results

The combustion efficiency was determined from the calculated temperature rise based on the static pressure measured at the end of the mixing chamber[16].

The effects of bypass ratio and dump momentum on combustion efficiency are presented in Figs. 4 and 5, respectively. The data were in general agreement with the very early SFRJ results and with the results of Natan and Netzer[14]; increasing bypass ratio at a fixed momentum ratio (Fig. 4) significantly improves combustion efficiency. In these tests the equivalence ratio was held approximately constant. To accomplish this, the fuel grain length had to be increased as the bypass ratio was increased, since G_a through the fuel port decreased, decreasing the fuel regression rate. Thus, it should be cautioned that as B_R was increased, G_a decreased and L_G increased; both effects having previously been shown to improve combustion efficiency[10].

At a given bypass ratio, decreasing the bypass air dump momentum generally increased the combustion efficiency (Fig. 5). At higher bypass momentum ratios the efficiency tended to increase and stabilize. It seems logical that increasing the momentum ratio increases penetration and mixing, thus combustion efficiency should increase and not decrease. In the post-firing examination of the motor it was

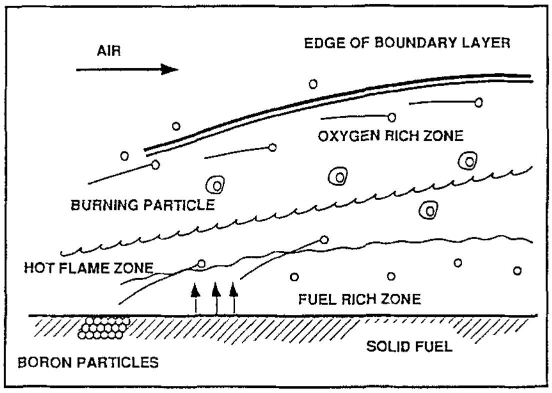

Figure 4. Effect of bypass ratio on combustion efficiency ($M_R = 0.23–0.27$, $P_c = 0.52–0.67$ MPa, $\bar{A}_{th} = 10.2\ cm^2$, $\dot{m}_a = 0.58$ kg/s, $\bar{T}_i = 592$ K, $\Phi_0 = 0.69$).

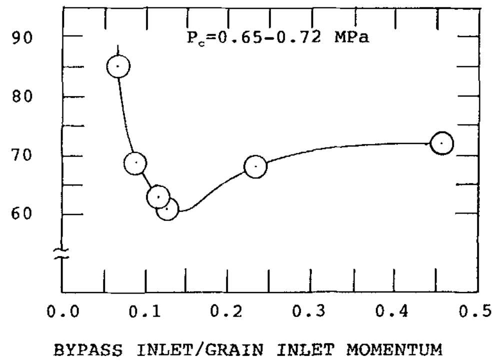

Figure 5. Effect of momentum ratio on combustion efficiency ($A_{th} = 10.2\ cm^2$, $B_R = 0.31$, $\bar{G}_a = 246\ kg/m^2s$, $L_G = 30.5$ cm, $\dot{m}_a = 0.59$ kg/s, $\bar{T}_i = 562$ K, $\Phi_0 = 0.69$).

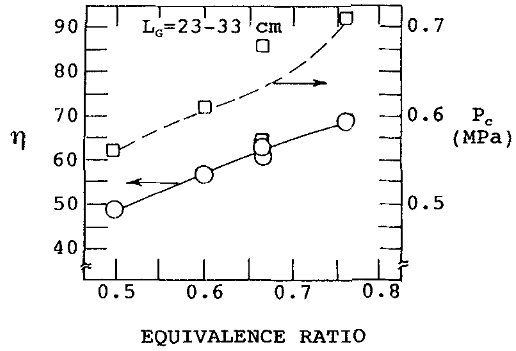

Figure 6. Effect of equivalence ratio on combuastion efficiency ($A_{th} = 10.3\ cm^2$, $B_R = 0.31$, $\bar{G}_a = 245\ kg/m^2s$, $\bar{M}_R = 0.12$, $\dot{m}_a = 0.59$ kg/s, $\bar{T}_i = 569$ K).

noticed that the boron carbide/residue on the motor walls increased with increasing bypass momentum. This indicated that the radial velocity towards the wall resulting from the bypass air injection probably caused the particles to collide with the wall and extinguish.

This peculiar behavior of the combustion efficiency with varying momentum ratio is thoroughly discussed in the theoretical part of the present research (Part II)[17].

Though the bypass air inlet temperature was considerably lower than the gas temperature at the mixing region, and significantly lower than the boron ignition temperature (~2000 K), the particles did not quench. On the contrary, the observed increase in combustion efficiency indicated that the burning rate of the particles was enhanced. This provides further justification of King's model[5], according to which, once the particle ignites, a high ambient oxygen molar fraction is sufficient for sustaining combustion of the particles even at low ambient temperatures.

Figure 6 shows the effect of equivalence ratio on combustion efficiency. In agreement with the data of Nabity, et al.[10] with a similar fuel composition, η increased with Φ_0 (or fuel grain length). As discussed in Ref. 10, much of the effect of equivalence ratio is thought to be due to the relative lengths of the recirculation zone and the boundary layer combustion region. The former produces larger particles, which are more difficult to burn completely. As seen in Fig. 6, the increased combustion efficiency with Φ_0 resulted in increased P_c. Increased P_c in itself can improve η through increased residence time.

To examine the effects of P_c, tests were conducted in which the throat area was varied, using an identical fuel composition except without the 5% Mg. The results are shown in Fig. 7. The increase in η with P_c in Fig. 6 is approximately twice that shown in Fig. 7, indicating that increasing Φ_0 (grain length) alone can significantly improve combustion efficiency.

These results provide a qualitative verification of the theoretical analysis of Natan und Gany[11–13]. Apparently there are two parameters for complete burning of the particles:

(1) The ignition process which is promoted by the thicker flame zone that is produced by decreasing the air mass flux through the grain part, and,

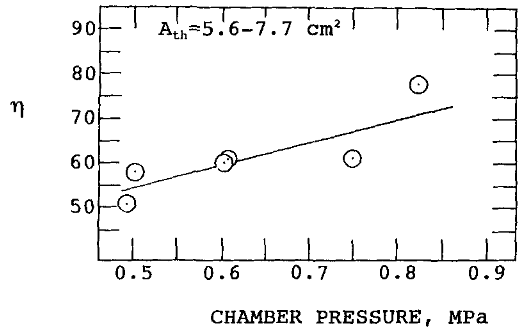

Figure 7. Effect of pressure on combustion efficiency (Φ_0 = 0.63–0.75, B_R = 0, $\bar{G}_a$ = 243 kg/m²s, L_G = 17.8 cm, $\bar{\dot{m}}_a$ = 0.37 kg/s, $\bar{T}_i$ = 598 K).

(2) The mixing of the already-ignited boron particles with the air that is provided by the introduction of bypass air.

The B_4C particles cast into the fuel grain had diameters between 0.5 μm–15 μm, with a mode at 4 μm. The particle size distribution measurements at the nozzle entrance most often showed a bi-modal or tri-modal distribution, with one mode between 2 μm–10 μm and another between 30 μm–100 μm. Another mode at a diameter less than 1.9 μm was probable, but was outside the accurate measurement range of the Malvern particle sizer. The larger particles were obviously the result of fuel surface agglomeration. Beam steering of the laser beam from density gradients in the flow prevented accurate determination of the mass-in-mode. In particular, particles larger than approximately 100 μm could not be accurately measured. Within these somewhat restrictive operating conditions, most of the *mass* of particulates was in the mode between 25 μm–70 μm, but most of the *number* of particles had diameters <1.9 μm. There were no major changes in the size distribution with bypass ratio, indicating that the increased combustion efficiency observed with increased bypass ratio resulted in part from increased consumption of the larger particles (>100 μm). A reduction in the mass percentage of the smallest (of low total mass) and largest particles would not be detected.

The highest combustion efficiencies attained (85%) corresponded to approximately 25% of the B_4C being unburned. The lowest combustion efficiency (36%) cannot be explained by having only unburned B_4C and Mg. Thus, even with the long mixing chamber lengths employed, some of the loss in combustion efficiency must have resulted from unburned HTPB. This is especially interesting since the combustion efficiency of HTPB decreases with increasing Φ_0, opposite to the effects observed with metals present. This implies that the particulate combustion improves with Φ_0 even more significantly than shown in Fig. 6.

4. Conclusions

The introduction of bypass air at the head-end of a mixing chamber of a boron carbide fueled solid-fuel ramjet can significantly increase the combustion efficiency of the motor. In general, combustion efficiency can be increased by using high bypass ratios, low dump momentum, low fuel port air mass flux, high chamber pressure and long fuel grains (high equivalence ratios).

Post-firing examination of the motor indicated that high dump momentum may result in collisions of the particles with the motor wall which can lead to their extinguishment and a reduction in the combustion efficiency.

Some of the reduction in combustion efficiency was due to incomplete combustion of HTPB rather than just to the incomplete burning of the particles.

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Symbols and Abbreviations

- A_{th} – Nozzle throat area
- B_R – Bypass ratio (mass flow rate of bypass air/total air flow rate)
- G_a – Air mass flux in the grain port
- L_G – Fuel grain length
- $\dot{m}_a$ – Total air mass flow rate
- M_R – Bypass dump momentum to inlet momentum ratio
- P_c – Average combustion pressure
- T_i – Average inlet air temperature (includes main, bypass and window purge air)
- $\bar{X}$ – Average value of X
- Φ_0 – Overall equivalence ratio

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