

Improving Reliability of High Power Quasi-CW Laser Diode Arrays Operating in Long Pulse Mode

Farzin Amzajerdian, Byron L. Meadows, Bruce W. Barnes, George E. Lockard, Upendra N. Singh, Michael J. Kavaya
NASA Langley Research Center, MS 468, Hampton, Virginia 23681-2199

Nathaniel R. Baker
Lockheed Martin Engineering and Science Company, Hampton, Virginia

Abstract – Operating high power laser diode arrays in long pulse regime of about 1 msec, which is required for pumping 2-micron thulium and holmium-based lasers, greatly limits their useful lifetime. This paper describes performance of laser diode arrays operating in long pulse mode and presents experimental data of the active region temperature and pulse-to-pulse thermal cycling that are the primary cause of their premature failure and rapid degradation. This paper will then offer a viable approach for determining the optimum design and operational parameters leading to the maximum attainable lifetime.

I. INTRODUCTION

Most moderate to high power solid state lasers require high-power quasi-CW laser diode arrays (LDAs) as their optical pump source. Compared with their low-power CW counterparts, these LDAs suffer from shorter lifetimes and are more susceptible to degradation and premature failure. This is mainly due to the excessive localized heating and substantial pulse-to-pulse thermal cycling of the laser active regions. The thermally-induced stresses are even more dramatic when the required pump pulsewidth is increased from 200 microseconds, applied to neodymium-based lasers, to about 1 millisecond required for thulium and holmium lasers [1-3].

Presently, lifetime testing of a number of LDAs from different suppliers is underway to assess the impact of long pulsewidth operation on the laser lifetime and reliability. The measurements to date indicate a lifetime of an order of magnitude shorter than reported lifetime for similar type of arrays operated at 200 microseconds pulsewidth. In addition to shorter lifetime, the arrays experience a high rate of catastrophic failure when operated in long pulse regime. A number of steps can be taken to improve the lifetime of LDAs such as operation at a de-rated level and a reasonably low temperature. Although these considerations will increase the lifetime and reliability of LDAs, an accurate trade analysis between LDA operational and design parameters is required in order to improve lifetime to an acceptably quantifiable level for lidar space missions using a thulium/holmium lasers. This paper discusses the experimental methodology and the resulting data revealing the thermal characteristics of different LDAs and provides the basis for a meaningful trade analysis leading to maximum attainable lifetime and reliability. Such a trade analysis can enable optimization of LDA specifications such as package type, number of bars per package and their pitch, operational

temperature, and operating parameters such repetition rate, pulsewidth, and applied current.

II. PERFORMANCE IN LONG PULSE MODE

To assess the impact of operation in the long pulse mode, a number of LDAs of different package types from different suppliers were subjected to a series of measurements including basic power and efficiency versus applied current, spectral characteristics, thermal properties, and package heat removal efficiency. A subset of these LDAs were then selected for initial lifetime testing in order to evaluate different commercially available LDAs, determine their lifetime expectancy, and to establish a baseline for improving their lifetime and reliability. Because of the lack of any dependable models, these initial lifetime tests were not accelerated and the LDAs were operated at the rated operational current and the expected pulse repetition rate for a space-based 2-micron lidar. The lifetime testing of the first set of LDAs began over two years ago (February 2004) and is now nearing its completion. The lifetime test facility developed for this work was originally capable of simultaneous measurement of 8 LDAs and then expanded to 12 LDAs and recently to 16 LDAs (Fig. 1).

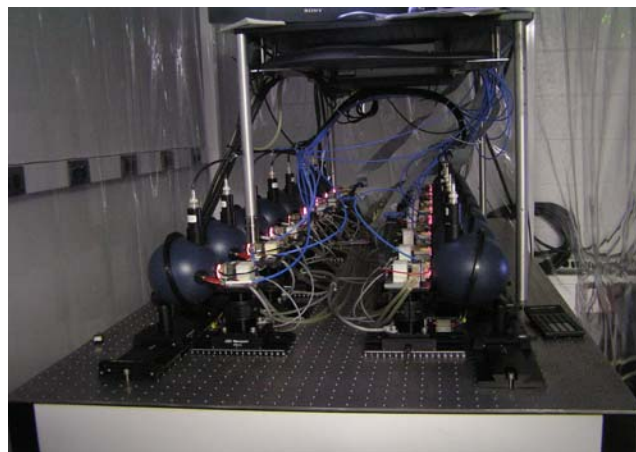


Figure 1. Laser diode array lifetime test facility.

The lifetime test facility is fully automated using a single computer to set operational and environmental parameters, acquire and archive data, flag anomalous readings, and generate a number of warning and status alert messages when necessary. All the LDA performance parameters are

continuously monitored and recorded using a common set of instruments for consistency and accurate comparative analysis and evaluation.

In order to provide a basis for comparative investigation of different LDAs, all the measured devices are 6-bar arrays with each bar rated at 100W for a total of 600W of peak power. All the arrays are tested under the general operational parameters chosen based on a notional earth-orbiting coherent Doppler lidar design listed below:

- Drive current 100 A
- Pulse duration 1 msec
- Rep. rate 12 Hz
- Heatsink temp. 25 deg. C

Fig. 2 is a representative of the lifetime test data showing the peak power versus number of shots for standard “A” and “G” package arrays from one of the major suppliers.

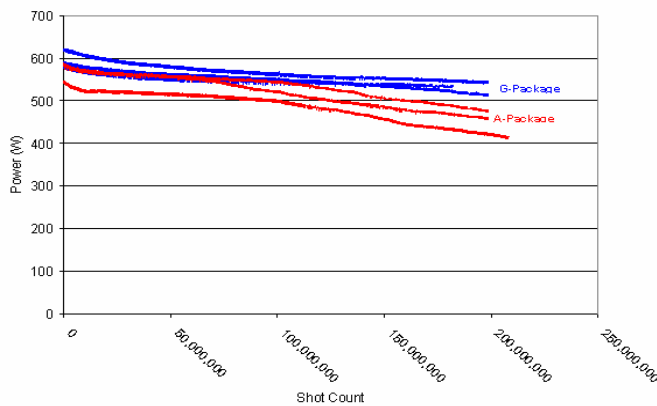


Figure 2. Example of lifetime test data of LDAs operating in long pulse mode.

As can be seen from Fig. 2, the arrays demonstrate a continuous gradual degradation with the number of shots for both package types. The degradation rate is somewhat lower for the G-package arrays but for both package types the lifetime is substantially shorter compared with reported data for operation at shorter pulsewidths (< 200 μsec). The anticipated lifetime is often represented through a statistical Weibull chart showing the probability of an array’s power dropping below a specified level. Fig. 3 shows a Weibull chart of the Fig. 2 data defining a 9% drop in output power as end of the life and a shape parameter (β) of 2.9. Although the number of data points in Fig. 3 is too small for a statically accurate representation of this particular array, it still provides useful information about its lifetime expectancy. Fig. 3 indicates that there is a 1% probability that this array will fail before it accumulates 30 million shots, 50% probability of reaching 120 M shots, and that 99.9% probability of failing by 220 million shots. This lifetime is inadequate for an Earth orbiting 2-micron lidar instrument which will require a lifetime of at least 1.0 billion shots.

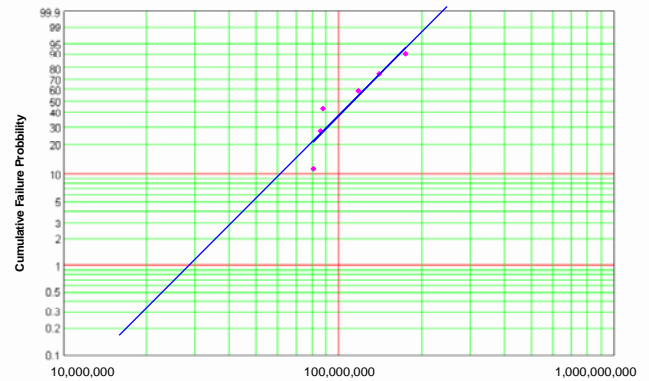


Figure 3. Weibull chart generated from the lifetime data illustrates the expected lifetime.

As noted earlier, the excessive heating and drastic thermal cycling resulting from operation over the long pulse duration of 1 msec are the cause of premature failure and rapid degradation of these LDAs [4-8]. Fig. 4 provides the measured junction temperature of a LDA as a function of pulsewidth showing an increase of about 10 degrees for 1 msec pulsewidth operation compared with 200 μsec. Fig. 5 illustrates the thermal cycling of a typical LDA where the temperature of the LDA face is measured by an infrared thermal camera.

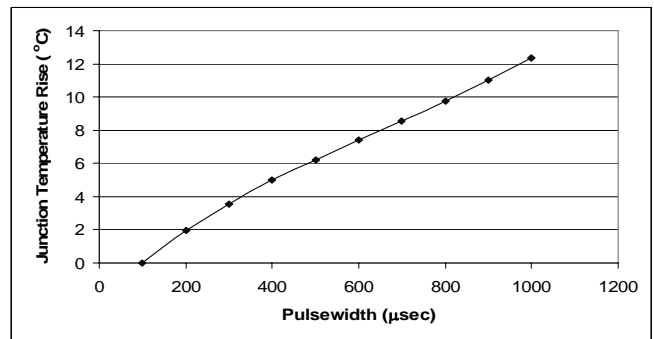


Figure 4. Junction temperature rise versus pulsewidth for a 6-bar laser diode array operating at 78 A.

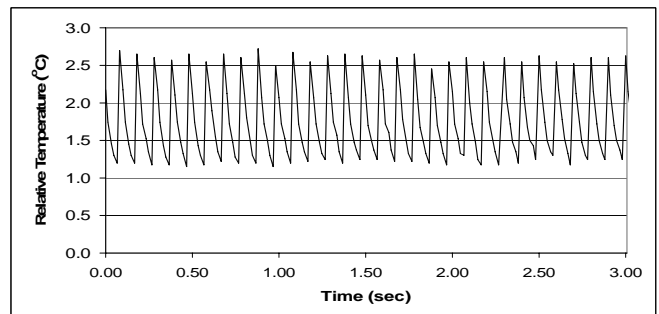


Figure 5. Thermal cycling of an LDA generating 1 msec pulses at 10 Hz

The current LDAs have an electrical to optical efficiency of about 50%. Therefore, when running a 6-bar LDA close to full rating, about 600 W of peak power is generated in the form of heat, (7.2W average at 1 msec pulse duration and 12 Hz prf). This excess energy primarily generated in the active area of the bars (light emitting surface), is quite substantial³⁻⁵. Given that the total active area at the surface of each bar is on the order of 1 micron wide by 10 mm long (10^{-4} cm²), yields a power density on the order of 10 kW/cm². It is this extreme excess heat and the rate and efficiency with which it is removed that drastically affects the laser diode performance, reliability and lifetime. The level of impact of the long pulse operation may be roughly estimated by an Arrhenius relationship written as:

$$\text{Lifetime } (\tau) \propto (T_a - T_b)^{-N} \text{Exp}(E_a/kT_a)$$

Where lifetime (τ) is expressed as a function of junction temperatures T_a and T_b measured immediately after and before the generated pulse, the activation energy (E_a) and Boltzmann's constant (k). The leading term accounts for the thermal cycling fatigue due to mismatch of thermal expansion coefficients of different package materials and various layers of the laser bar. The power N in the expression above can have a value between 2 and 5 depending on the materials properties based on the Manson-Coffin law for thermal fatigue. It is obvious from this Arrhenius equation that reducing the temperature difference before and after the pulse is the key for increasing the lifetime to an acceptable level. This may be achieved through careful selection of the LDA package type, specifications of the array considering the pumping requirements, and defining its operational parameters. Table 1 below summarizes the trade space and design and operational specifications that need to be carefully considered based on the solid state laser pump requirements and the lidar mission objectives.

TABLE 1. TRADE SPACE FOR INCREASING THE LIFETIME AND IMPROVING THE RELIABILITY OF LDAS OPERATING IN LONG PULSE MODE.

Trade Space	Specifications	Parameters/Selections
Package	Geometry	A or G package style
	Architecture	Bars in Groove, Rack & Stack, Stacked Subassemblies (see Fig. 10)
	Heatsink Materials	BeO, Cu, CuW (see Fig. 10)
Bar	Efficiency	Wafer architecture and Epitaxy
	Fill factor	No. of emitters per bar
Array	No. of Bars	Constrained by pump power requirements
	Pitch	Constrained by pump brightness requirements
Operational Parameters	Drive Current (de-rating)	Constrained by pump power requirements
	Pulsewidth	Constrained by pump power and system efficiency requirements
	Pulse Repetition Rate	Constrained by science product requirements
	Sink Temperature	Constrained by spacecraft heat management system

III. THERMAL MEASUREMENTS

Several experimental tests have been developed to investigate the thermal characteristics of high power LDAs in order to evaluate various package designs and define the best operating parameters. These measurements also facilitate the technology advancement activities leading to the development of new LDAs with improved reliability and lifetime. The thermal characterization of LDAs includes the thermal imaging of the facets, spectral shift and broadening measurements, and a forward voltage measurement technique we refer to as the "Forward Voltage-Short Pulse" (FV-SP) technique. The FV-SP technique is devised based on a conventional measurement used for electrical diodes, light-emitting diodes, and continuous-wave laser diodes. The FV-SP measurements are particularly useful in providing the necessary data for a meaningful trade analysis leading to maximum attainable lifetime and reliability. Such a trade analysis can encompass all the LDA design and operational parameters as summarized in Table 1 in addition to facilitating quantitative comparison between vendors and packages and screening of devices within a given fabrication run.

The FV-SP measurement utilizes the diode characteristics of the LDA to measure its junction temperature. In this measurements, a series of relatively short and low current pulses, compared with the actual drive current, are applied to the LDA and the resultant voltage are measured with a high degree of precision (Fig. 6). The measured voltage drop across the array is related to the junction temperature through the diode I-V equation.

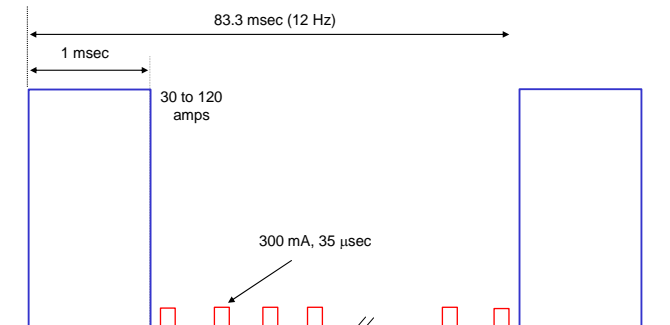


Figure 6. The Forward Voltage-Short Pulse technique for measuring the LDA junction temperature.

One of the main advantages of this technique is its ability to obtain the junction temperature before and after each LDA pulse. Another benefit of this measurement technique is its ability to determine the junction temperature while running the LDA at any operational parameters without tedious post processing required by other techniques such as time-resolved spectral measurements. Fig. 7 is an example of the FV-SP measurements showing the peak junction temperature before and after the generated pulses and the thermal impedance (ratio of junction temp. rise to dissipated heat) as a function of drive current. It can be seen from these plots

that the temperature rise during the pulse is almost a linear function of applied current. Using the measured junction temperatures in the Arrhenius expression of previous section, the relative impact of current de-rating can be estimated. Fig. 8 illustrates the lifetime improvement resulting from reducing applied current. It worth noting that high power quasi-CW laser diode arrays are complex electro-optical components and thus their lifetimes do not follow well defined or known predictable models such as Arrhenius relationships unless considerable statistical data is available for accurately specifying the activation energy (E_a) and thermal fatigue constant (N) [9-12]. However, results such as shown in Fig. 8 can still provide useful information by enabling a determination of the magnitude of improvement that can result from various measures for reducing the junction temperature and thermal cycling. Fig. 8 clearly shows that up to an order of magnitude improvement in lifetime may result from de-rating by about 30% (i.e., operating at 70 A). Fig. 9 is another example of the FV-SP measurements showing the thermal impedance of a LDA versus pulsewidth while maintaining a fixed duty factor (pulsewidth X rep. rate = Const.). Relative expected lifetime is also shown in this figure and indicates that a two order of magnitude longer lifetime is possible when operating at 200 μ sec and shorter pulses compared with 1 msec operation.

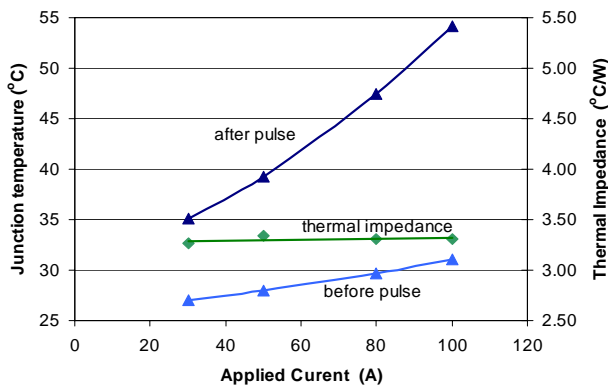


Figure 7. Before and after pulse junction temperatures measured using the Forward Voltage-Short Pulse (FV-SP) technique.

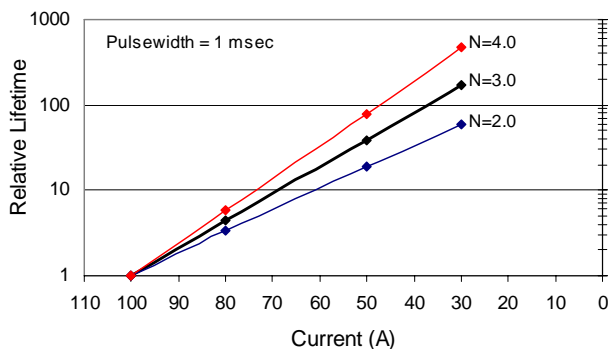


Figure 8. Relative lifetime expectancy versus applied current for different values of thermal fatigue constants.

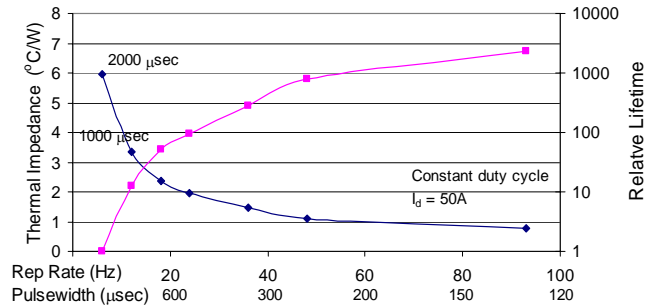


Figure 9. Thermal impedance and relative lifetime as a function of pulse width and repetition rate while keeping the total average power constant.

As Figs. 7-9 illustrate, using the thermal data obtained from FV-SP measurements in an Arrhenius model allows for a reasonable analysis of the LDA performance and determining its optimum operational parameters for achieving the maximum possible lifetime while meeting the lidar and the mission requirements

IV. ADVANCED PACKAGE MATERIALS

Although careful specification of the array and accurate definition of its optimum operational parameters will significantly increase the expected lifetime, further advancement of the technology, particularly in the area of packaging, may be necessary to enable a viable 2-micron laser remote sensing system requiring long duration autonomous operation such as an earth orbiting instrument. Shown in Fig. 10 are the typical materials and general construction of the most common high power LDAs. The active region of the LDA, where heat is generated, is only about 1 micron wide, located about 3 microns from the p side of the bar. The bars are about 0.1 mm wide and spaced about 0.4 mm to 0.5 mm from each other. Waste energy in the form of heat must be conductively transferred into the solder material and from there into the heat sink material (typically BeO or CuW) as rapidly as possible. The solder material of choice is a soft Indium alloy for its ductile property allowing the bar and the heat sink to expand or contract at different rate with temperature.

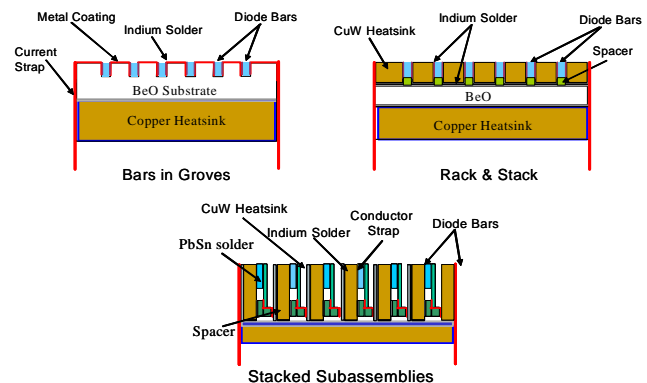


Figure 10. Conventional LDA packages.

Using a material, which possesses a higher thermal conductivity and relatively comparable coefficient of thermal expansion (CTE), should result in a device with both lower thermal resistance and induced mechanical stress. Table II shows the salient properties of the materials commonly used in LDA packages and some advanced materials being considered for improving heat transfer, thereby improving the performance and lifetime of LDAs [13,14]. One such material is CVD Diamond, chosen for its high heat transfer and low CTE. Diodes using Diamond heat sinks were fabricated and compared to standard package LDAs using the same experimental construction technique. The experimental Diamond package devices were 6-bar arrays (600W) fabricated using the rack and stack package style shown in Figure 10 with A-type geometry. Measurements of these experimental devices produced very promising data showing 17% reduction in thermal impedance compared to the same package using conventional CuW heatsinks. Development of the Diamond package arrays and the results of laboratory tests were previously reported [13,15].

Additionally important to reducing mechanical stress is consideration of the use of soft solders which are highly pliable with a relatively low melting point (~ 160°C). Post life test analysis indicates that solder deformation caused solder roll-over, in turn creating voids, which increase thermal resistance. When coupled with built-in stress due to fabrication, such roll over, in time often obstructs emitters, leading to increased heating, or extends across the bar from anode to cathode causing bar shorts which eventually result in contaminations to the emitter face and localized hot spots, further degrading performance.

TABLE II. THERMAL PROPERTIES OF THE MATERIALS BEING CONSIDERED COMPARED WITH CURRENT PACKAGE MATERIALS.

	Material	Coefficient of Thermal Expansion (m/m°C)	Thermal Conductivity (W/m-K)
Standard	GaAs (wafer material)	6.8×10^{-6}	46-55
	Indium Solder	29×10^{-6}	86
	BeO	8×10^{-6}	260
	Copper/CuW	$6 - 8 \times 10^{-6}$	200-250
Advanced	Diamond	1×10^{-6}	1100-1600
	Carbon-Carbon Composites	$1-6 \times 10^{-6}$	300-600
	Metal Matrix Composites	$6-16 \times 10^{-6}$	820-890
	AuSn Solder	16×10^{-6}	58

IV. CONCLUSION

Measurements to date indicate that operating off-the-shelf LDAs over long pulse duration regime of the order of 1 msec

substantially degrade their performance. The LDA lifetime can be increased by careful specification of the LDA and by determining its optimum operational parameters for maximum lifetime by considering the solid state laser pump requirements and the mission objectives. There are also several promising LDA packaging technologies that can address the thermal issues of high power arrays leading to more reliable and longer lifetime. Improvement of LDA lifetime and reliability require accurate characterization of their critical thermal properties, primarily the junction temperature of their bars and thermal impedance of their package. Therefore, a series of measurement techniques for quantifying the thermal properties of the LDAs were employed. These measurement techniques include spectral shift and broadening measurements, time-resolved spectral measurement, and high spatial resolution thermal imaging of the LDA facet. In addition to these measurements, a new technique was devised, that we refer to as "Forward Voltage-Short Pulse" (FV-SP) technique. The FV-SP technique is based on a conventional measurement used for electrical diodes, light-emitting diodes, and continuous-wave laser diodes. FV-SP measurements are particularly useful in providing the necessary data for a meaningful trade analysis leading to maximum attainable lifetime and reliability. Preliminary results of the FV-SP have already provided valuable criteria for de-rating of the LDAs and specifying its operational temperature. This measurement also provides useful data for evaluating different package types from various suppliers and specifying their design (ex., geometry, number of bars, and pitch).

In parallel with the characterization and analyses efforts towards maximizing the lifetime of existing LDAs, work on advancing the technology for addressing failure mechanisms in a more fundamental fashion is ongoing. A preliminary experimentation with CVD diamond materials provided promising results showing about 17% decrease in thermal impedance and improved operational stability as measured in spectral response. Current work also includes developing carbon and metal matrix composites tailored to yield high, and possibly directional, heat transfer coefficients while more closely matching the CTE of GaAs, thus reducing built-in stress induced during fabrication and perhaps eliminating the thermal-induced stresses during operation. The use of CTE-matched materials can also allow for substituting the soft indium solder with thin hard solder materials such as AuSn. Indium solder has been implicated as a cause of premature array failure and has also been a suspect source of contamination of solid state laser crystal or optical surfaces of Lidar/Laser system. It is strongly held that such work will in time lead to longer lived, more operationally stable and reliable LDAs.

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