2.B Uniform Liquid-Fuel Layer Produced in a Cryogenic Target by a Time-Dependent Thermal Gradient

In inertial fusion experiments, it is possible to achieve a higher-density compression by starting with the DT fuel in a condensed state instead of a gaseous state at room temperature. Because of the uniformity requirements of direct-drive inertial fusion, the DT condensate must be in the form of a highly uniform and spherically symmetric layer on the interior surface of the cryogenically cooled fuel capsule. Prior efforts to fabricate such a target have included instant refreeze of the fuel after vaporization with a laser pulse,[1,2] absorption of the fuel in a foam layer,[3-5] redistribution of the fuel by beta-decay heating,[6,7] and the application of a static thermal gradient to overcome gravity-induced sag of liquid fuel.[8-13] A unique set of difficulties is encountered in deploying each of these techniques in the target chamber of a multibeam laser. In this study, a time-dependent thermal gradient is applied to a target that has been cooled by helium gas jets. The liquid-DT fuel, initially thicker at the bottom of the shell, is redistributed, and a momentary state of uniformity is observed. Continuing its motion, the fuel subsequently becomes thicker at the top of the shell. Suitable timing of the applied thermal gradient can provide fuel-layer uniformity at the moment the drive laser is fired. This method works in the presence of room-temperature thermal radiation, while not obstructing any of the beams of the drive laser. The necessity for a retractable isothermal shroud (used in instant refreeze and other techniques) is thus eliminated. In addition, this method works for thicker condensed-DT layers than can be made uniform with the instant-refreeze technique.

Several studies[8-13] have described how DT or D_2 liquid should become uniformly distributed on the wall of a shell when a suitable static thermal gradient is applied to overcome gravity-induced nonuniformity. The phenomenon is explained as a balance among gravity, surface tension, and a dynamic equilibrium of evaporation, recondensation, and liquid flow. In the case of DT, a multicomponent fluid (D_2, T_2, and DT), some fractionation occurs, with the warmest spots developing the highest concentrations of T_2, the least volatile component. A prediction of this model, that with D_2 (a single-component fluid) uniformity is achieved by making the top of the target colder than the bottom, whereas with DT, the reverse is true, was demonstrated experimentally by Kim and Krahn.[8] Fuel uniformity was observed in only a single view, however, leaving open the possibility that, had the target been viewed from another direction, a nonuniform fuel distribution might have been seen. As in the Kim and Krahn study, the work described here employs opposing helium gas jets to cool the target and a three-axis translator to position the target between the nozzles. Important differences in this study include the use of two-view interferometry, ohmic heating of the nozzles to apply the thermal gradient, a greater solid angle for incident room-temperature thermal radiation, a lower background pressure, and the finding that a time-dependent thermal gradient is required to achieve fuel uniformity.

The nozzle assembly, shown in Fig. 40.20, meets the requirements of (1) being able to cool a target to the freezing point of DT, (2) providing a vertical thermal gradient sufficient to produce liquid-DT-layer uniformity just above the freezing point, (3) being geometrically arranged so as not to obstruct any of the 24 beams of the OMEGA laser, and (4) being easily replaceable. This assembly is attached to a copper rod cooled by a liquid-helium cryostat. The base block, made of tellurium-copper, provides good thermal contact between the copper rod and the high-purity (99.99%) copper tubes leading to the nozzles. Lower-purity copper tubing was tried, but it lacked sufficient thermal conductivity. The nozzles are cylinders of electroformed copper, though short pieces of stainless steel tubing were also found to work. The inside diameter of the nozzles, ~100 μm, is not critical: a nozzle

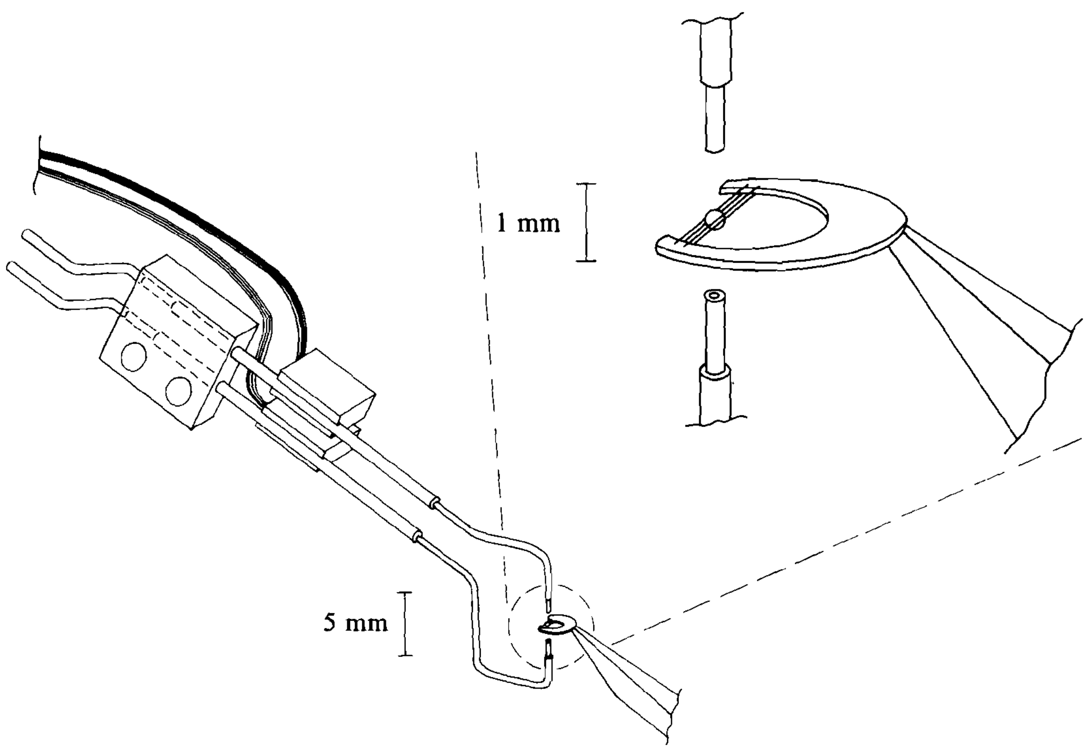

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Fig. 40.20
Nozzle assembly with target and its support. When installed, the nozzles are vertical, and the target is positioned independently between the nozzles. The parts are precisely arranged so as not to obstruct the 24 beams of the OMEGA laser. Tubing parts are bent on precise fixtures and then clamped together on another fixture for soldering. The heater-thermometer assemblies are soldered on last.

diameter of 400 μm was also found to work for a 250-μm-diameter target. The main constraint on nozzle diameter is that the outer edge not obstruct beams of the OMEGA laser. Larger-diameter nozzles must be placed farther from the target, reducing cooling efficiency and requiring a greater flow of helium gas. The helium gas-supply tubes are stainless steel, bent to fit into a quickly demountable fixture sealed with compressed indium. Attached to each of the copper tubes is a heater-thermometer assembly with a silicon-diode thermometer and a heater consisting of coiled resistance wire. The thermometers are for diagnostic purposes and could be omitted in the future, since observations of freezing of the fuel provide adequate temperature data.

Preparing for application of the time-dependent thermal gradient entails setting up suitable ambient conditions of target position, helium gas flow, and nozzle temperature. After centering the target reasonably well (to ~ 50 μm) between the nozzles, gas flow is established using a pair of flow controllers. The initial flows of 30 to 60 μg/s to each nozzle can later be reduced. Heat exchangers cool the He gas to the temperature of the copper support rod (5°K in the absence of applied heat) before it enters the nozzle supply tubes. This flow of gas freezes the DT in the target. Sufficient heat is then supplied to the copper support rod to barely melt the DT, using a temperature controller. Next a series of small adjustments is made, in target position, temperature of the copper support rod, and finally differential heat to the nozzles, with the goal of getting the fuel as close as possible to a uniform state while just above the freezing point. Fuel uniformity is easily assessed at this stage by observing the interferometric video images of both views of the target with the interferometer set up for a constant-phase background. At this point it is possible to obtain uniformity in one view or the other, but with the alternative view showing a high degree of nonuniformity.

After these initial adjustments of the ambient conditions, a time-dependent thermal gradient is imposed using a repetitive cycle of several-seconds duration. In this cycle, the current applied to the upper nozzle heater is given a step increase, lasting 0.5 s or more, or the lower nozzle heater is given a step decrease, or both. As this cycle continues, further small adjustments are made in all the aforementioned quantities until the degree of momentary fuel uniformity is satisfactory, and one is assured that the fuel, when in the uniform state, is as close to the freezing point as possible, and gas flow is minimized. The final positioning adjustments of the target with respect to the nozzles are in 2- to 5-μm steps. The position must be adjusted to this precision in both lateral directions. As fuel uniformity is now a transient state, a video recorder is employed to help assess the uniformity and repeatability of this state.

Observation of fuel-layer uniformity requires a high degree of uniformity of the outer shell. This is assured by the shell-selection process prior to permeation of the shell with fuel. The shell is preselected[14] for wall thickness, and then rotated about two axes in a Mach-Zehnder interferometer so that uniformity is observed from three orthogonal directions. After permeation the shell is mounted, usually between four submicron spider webs,[15] uniformly coated with 0.1 μm of parylene, and recharacterized in the cryogenic apparatus. For each step in the characterization process, interferograms are obtained from two directions at right angles to each other. A pair of shearing interferometers of new design is employed.[16] To assess uniformity, a constant-phase background is used, producing interference fringes that are circular and concentric if the target is uniform. If reasonable uniformity is found, a tilt is introduced in an interferometer mirror, producing a background fringe pattern of parallel lines. This "tilted-phase" interferogram allows greater accuracy in determining such parameters as wall thickness, fuel-gas density, or fraction of fuel condensed.

Complete characterization of a target is a three-step process. At each step, constant-phase and tilted-phase interferograms are taken from both directions. The first step is to use sufficiently cold gas flow from the nozzles to freeze all the fuel on the top or bottom of the target, allowing redetermination of the wall thickness and uniformity of the shell portion that is free of fuel. Next, the target is warmed, and interferograms of the gaseous state are taken to determine the fuel density, and therefore the total fuel content. Finally, interferograms of the uniform condensed state are taken, from which fuel uniformity and fraction condensed are determined. These three steps are illustrated in Fig. 40.21.

To assess the fuel content and distribution in a target, interferograms are matched with templates generated using a ray-tracing computation. For this computation the input parameters specific to the target are shell diameter, wall thickness, shell refractive index, fuel density in the gaseous state, fraction condensed, and fuel refractive index.[17,18] Templates can also be generated for low-order modes of fuel nonuniformity, especially decentration of a specified magnitude and direction. The parameters specific to the interferometer are wavelength, wave-front tilt (i.e., number of background fringes per unit length along each of the two axes of the interferogram), additive phase, magnification, and the focal ratio (*f*-number) of the collecting lens. The focal ratio determines the extent of a dark ring inside the edge of the target corresponding to rays refracted by the target beyond the edge of the collecting lens. The template generated is an array of 240×256 pixels showing points of constant phase on the wave front and the edge of the target. To test a match between a template and an image, the image (480×512 pixels, each with 256 levels) may be live or recorded on disk memory. The template, in color, is superimposed over the black-and-white image using a video monitor.

The central portion of each interferogram yields the optical path through the center of the target with a nonuniqueness of an integer number of waves. For example, if the observed fringe at the center of the target is dark and the central background fringe is light, the optical path through the center of the target is $(m + 1/2)$ waves, where m is an unknown integer. In practice, comparison with the template over the whole field of view is usually sufficient to eliminate the nonuniqueness. First, an apparently acceptable match of a template to

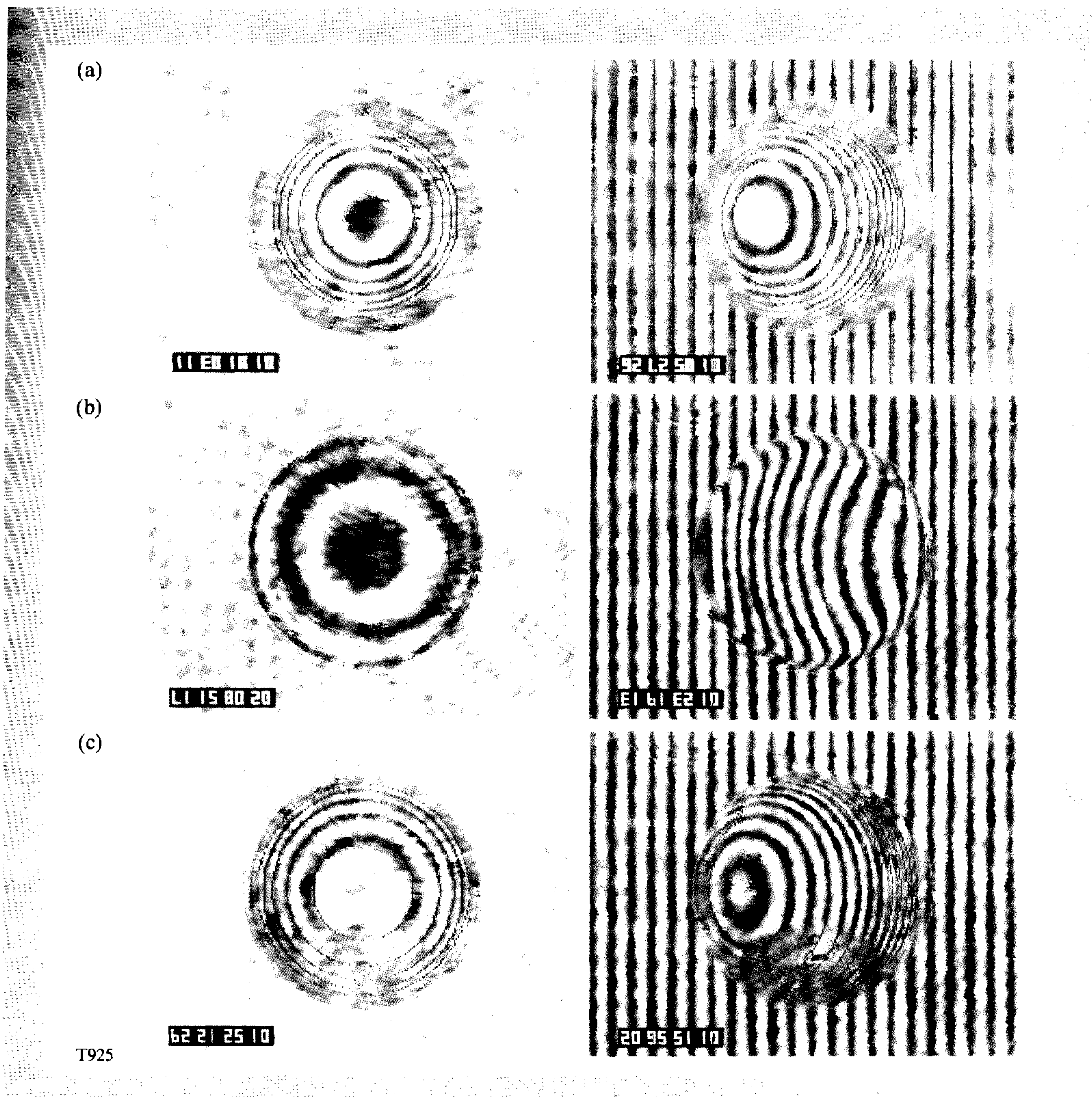

Fig. 40.21
Interferograms and templates (from one of the two views) needed to fully characterize a target. The constant-phase interferograms on the right demonstrate uniformity, while the tilted-phase interferograms on the left are used to measure target parameters by matching the templates to them. (a) Fuel is all frozen on top. Template match indicates the wall thickness* is 4.62 ± 0.1 μm. (b) Fuel is in the gaseous state. The pressure** of DT is found to be 171 ± 3 atm. (c) Fuel is momentarily in a uniform liquid layer with ~98% condensed. The other view also shows uniformity. The match of the templates to the interferograms is remarkably good in every detail. The templates may be recognized as thin uniform lines.
*This assumes precise knowledge of the index of refraction of the shell material.
**By "pressure" we mean here the pressure that would exist if DT obeyed the ideal gas law. In reality, this is a measurement of gas density.

an image is found with the fringes matching both outside and at the center of the target. Then the parameter being determined is increased or decreased by enough to shift the template by one fringe at the center of the target. The template will still be a good match near the center of the target. In most cases, however, the changed parameter can be accepted or rejected based on whether the match away from the center has improved or worsened. If one is still not certain of the uniqueness of the match, this can be resolved by changing the illumination wavelength and going through the matching process again. This technique enables the target parameter to be characterized to a high degree of accuracy, with errors corresponding to optical path changes approaching one tenth of the illumination wavelength.

By observing the freezing of the fuel at a variety of gas flows and nozzle temperatures, a useful equation can be obtained for target temperature as a function of these parameters. Since the target is exposed to room-temperature thermal radiation from nearly all directions, it absorbs power, $4\pi r^2\sigma T_r^4\epsilon$, where T_r is the (absolute) room temperature, r is the target radius, σ is the Stefan-Boltzmann constant, and ϵ is the emissivity of the target. This power is removed by the cooling power of the helium gas stream, $feC(T_n-T_t)$, where f is the total gas flow (mass per unit time), C is the specific heat (per unit mass) of the gas, T_t is the target temperature, T_n is the nozzle temperature, and e is the efficiency of the gas stream for cooling the target. Equating these, the target temperature is found to be

$$T_t = T_n + \frac{4\pi r^2\sigma T_r^4\epsilon}{feC} \quad . \tag{1}$$

Although it assumes equal flows and temperatures for the two nozzles, this equation is readily generalized to the case of unequal values of these parameters. To use Eq. (1), we must first obtain the ratio e/ϵ, other quantities here being known. This is done by obtaining a series of points for which the target is at the triple point[17] of DT, 19.8°K. For each setting of the flow controllers (equal flows from the two nozzles were used), the mean nozzle temperature was found that would just solidify or just melt the fuel. (These were slightly different temperatures; both are plotted.) The temperature variation was achieved by heating the copper rod supporting the nozzle assembly, so that the two nozzle temperatures were nearly equal. The data, plotted in Fig. 40.22, may be fit with a straight line by rewriting Eq. (1) as an expression for T_n. The ratio e/ϵ is then found from the slope of the line to be 0.035 for the particular nozzle assembly and target used in this measurement. It should be noted that the line intersects the vertical axis at the temperature of the target, implying that the nozzles are at the measured temperatures and there is no significant heating of the nozzles by radiation or by conduction through the gas in the chamber. Having determined the ratio e/ϵ, it is reasonable to use a generalized form of Eq. (1) to estimate the target temperature for other combinations of flow and nozzle temperature.

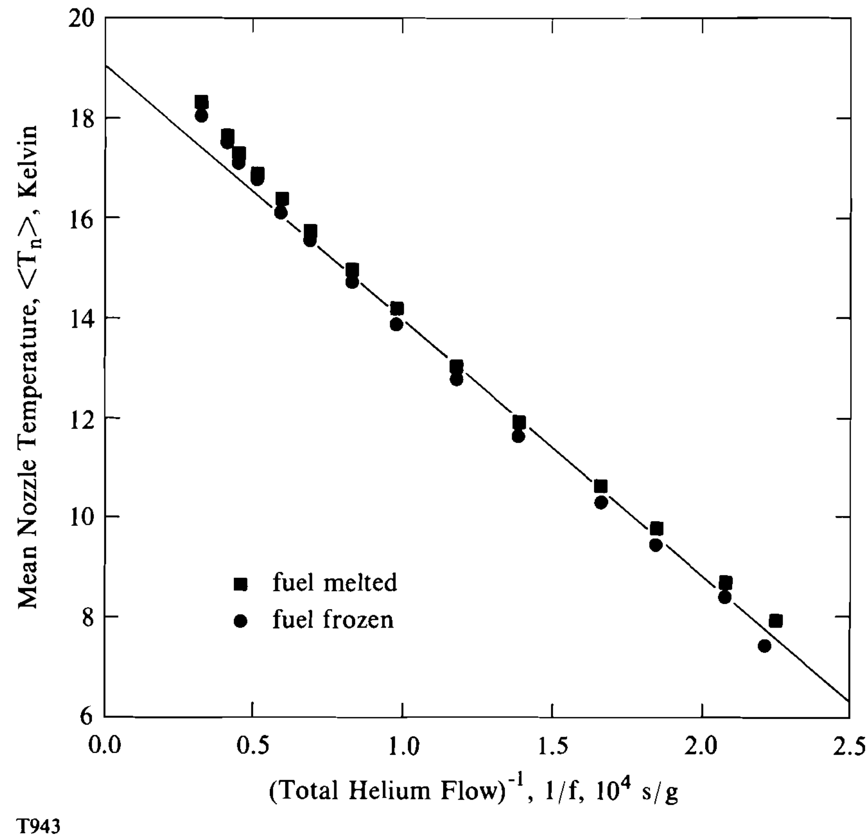

Fig. 40.22
Mean nozzle temperature required to freeze the DT fuel and to remelt the fuel as a function of f^{-1}. The solid line is a fit of Eq. (1) to the data giving most weight to the lower values of flow, which are used for obtaining uniform fuel layers. The intercept to the vertical axis is within the 1°K uncertainty in the thermometer calibration of equaling the 19.8°K triple point of DT. The slope of the line indicates $e/\epsilon = 0.035$. The 251-μm-diameter target is centered between the nozzles, which are 1.8 mm apart and have an inside diameter of 130 μm.

Fuel uniformity in both views is demonstrated in Fig. 40.23. Uniformity is achieved 270±30 ms after applying increased current to the upper nozzle heater. This time depends upon the exact ambient conditions. The ambient conditions are set up so that a reduction of ~0.2°K in the target temperature would cause the fuel to freeze. Under such conditions, the fraction of fuel condensed when uniformity is achieved is in the range of 95% to 98% as measured by template matching to the tilted-phase interferograms. This percentage can probably be maximized by a strategy of increasing the thermal gradient with no change in the mean target temperature. To implement this strategy, heat to the lower nozzle would be decreased at the same moment that heat to the upper nozzle is increased. The helium gas

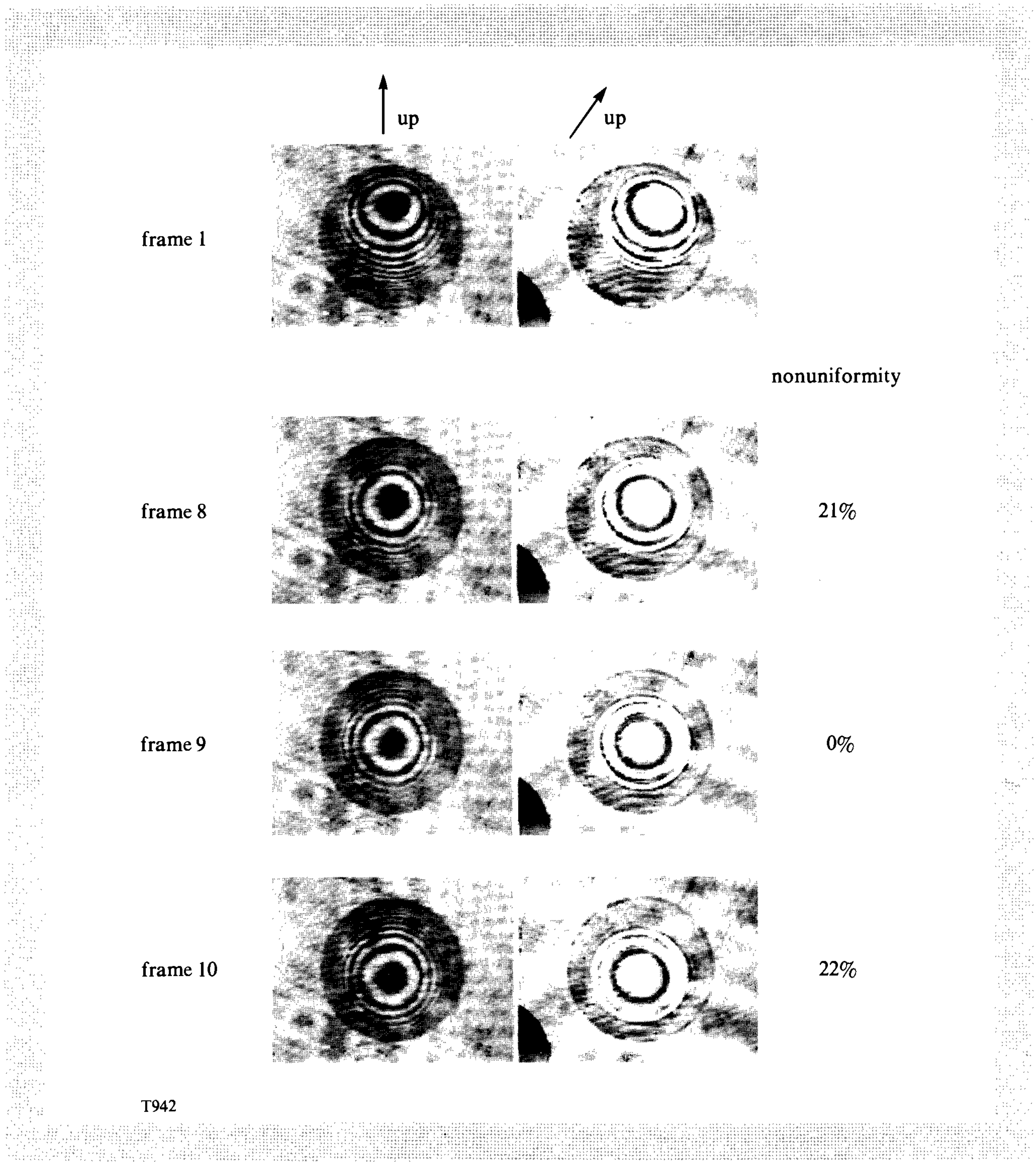

Fig. 40.23
Interferograms demonstrating transient uniformity of the fuel. The left and right images in each pair show the two views, which are at right angles to each other, obtained simultaneously. The upper pair of images show the ambient state before application of the thermal gradient. The three lower pairs of images show sequential video frames, 33 ms apart, as the fuel passes through the state of uniformity. Uniformity is found to occur 270 ± 130 ms after application of the increased thermal gradient.

flow to produce the uniformity seen in Fig. 40.23 was 30 μg/s from each nozzle. This produced a background pressure in the experimental chamber of 0.5 mTorr. The background pressure is dependent upon pumping speed; in this case, a 10-cm diffusion pump was used with a liquid-nitrogen-cooled baffle. It remains to be determined whether the amount of helium gas near the target will interfere with the implosion process. Repeatability of this process to ± 30 ms has been demonstrated in these recordings. Efforts will be made to reduce this uncertainty by synchronizing the application of the thermal gradient with the simultaneous recording of the two views.

In conclusion, a transient state of uniformly distributed condensed fuel has been demonstrated in high-pressure DT targets by application of a time-dependent thermal gradient. The technique works in the presence of room-temperature thermal radiation and could be deployed in the target chamber of the OMEGA laser without obstructing any of the beams. A difficulty inherent in this method is the precise adjustment required of the target position with respect to the cold helium gas jets. This method overcomes two difficulties with the instant-refreeze method of obtaining fuel uniformity: it eliminates the need for a retractable isothermal shroud and produces uniformity in targets with much higher pressures than can be made uniform with the instant-refreeze technique. In the process of developing this technique, improved methods of target characterization have been introduced.

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