Fuel Holdup and Component Diffusivity in a Cooled Cylindrical Tank

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The precipitation of solid waxes from aircraft jet fuels in cylindrical tanks (pod wing tanks) at the low temperatures encountered in high-altitude flight has been experimentally modeled. The techniques used were a direct measurement of optical opacity and holdup in a simulated wing tank, ultrasound imaging, and diffusion measurements based on nuclear magnetic resonance. The work is intended to show the applicability of these techniques to the study of holdup in realistic systems, and to attempt qualitative correlation between their results. The morphology of the fuel precipitate and its permeability to the liquid fuel component are found to depend on cooling rate as well as on the final temperature.

Introduction

THIS study deals with fuel holdup in jet aircraft operating on long missions at temperatures near or below −40°C (e.g., high-altitude and polar flights). The problem is well known; some less volatile components (such as waxes) of the chilled fuel may solidify and become unable to drain and may also inhibit drainage of the remaining liquid fuel. The amount held up is by no means insignificant and may result in substantial degradation of the mission.

This bottleneck problem occurs in gravity-drained wing tanks with the saving feature that fuel, in whatever form, that makes it through the coarse inlet screen and to the boost pump impeller can usually be forwarded through the fuel lines to the engine fuel pump.[1] The problem of the prediction of holdup conditions is complicated by the fuel flow: wax that is mechanically fluidized in a chilled fuel may be usable, whereas wax not fluidized might pack in a corner of the tank and be held up. More will be said later about the micro and macroprocesses occurring in the holdup problem.

This problem has typically been studied with wing-tank simulators subjected to environmental conditions resembling the mission. They are of substantial size and realistic tank geometry, usually full scale in height but reduced in other dimensions. Their material construction and interior finish are those of real tanks.[2] The questions addressed by simulations of this kind are under what conditions does holdup occur and to what extent does it interfere with the full use of the fuel.

In addition to draining the tank at appropriate stages in the mission, the simulator also measures temperatures at various points in its interior. But detailed knowledge of the precipitation and disposition of solids is elusive, partly because of the reduced visibility after the fuel becomes cloudy. That optical techniques are nearly useless in the study of fuel behavior below the cloud point (e.g., via ASTM D2500 definition) may be concluded from Fig. 1, photographs taken of the simulator at NASA Lewis, now at Wright-Patterson Air Force Base. Figure 1a demonstrates a visibility of a few feet within warmer fuel, whereas in Fig. 1b, the visibility in colder, barely translucent fuel is limited to about 1 in.

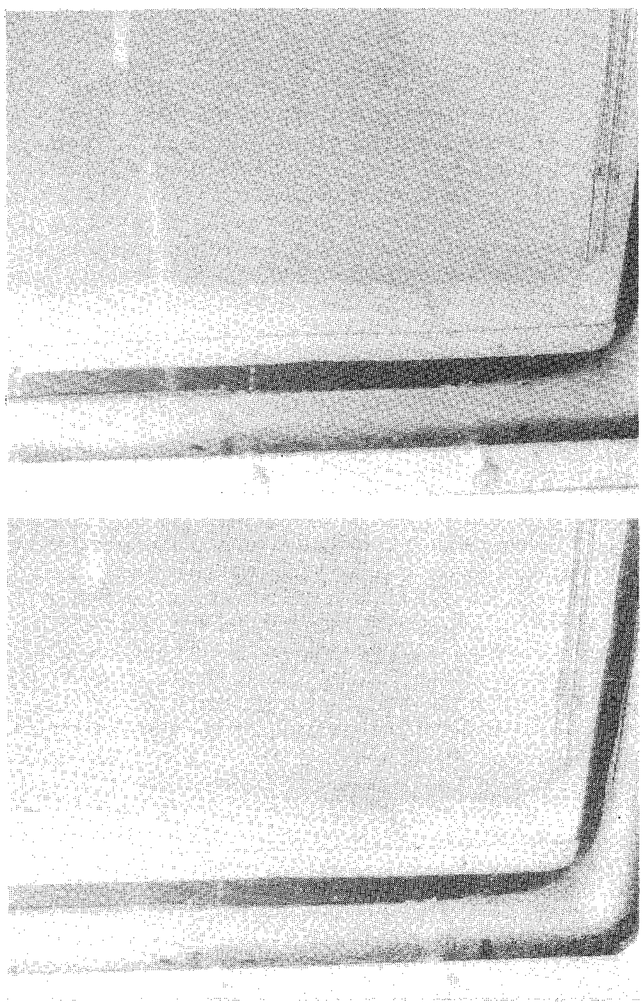

Fig. 1 Transparent and translucent fuel situations in a wing-tank simulator.

Received June 25, 1988; revision received Nov. 3, 1988.

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It is known that while the temperature profile itself is the main determinant of holdup, the fuel's density profile offers important additional information relating to solids formation. A third profile, the velocity profile, may be important because it could be a factor in whether solids are fluidized. A full velocity (flow) profile in a quiescent/draining tank simulation experiment has, to our knowledge, not been obtained. Even if some or all of these profiles could become empirically available, an understanding of the underlying transport science must be desirable in any case and should be pursued, both to give a theoretical underpinning to the practical studies and to validate the understanding of the data, adding assurance to the overall enterprise.

Generic Cooling Process

Under slow cooling conditions, conduction may be the only important heat-transfer mode. Description with solutions of the heat conduction equation would require conductivity, density, and specific heat values. Conductivity normally varies little with temperature. This might be expected in two-phase mixtures, as well as for specific heat. Density typically varies by about 1×10^{-3}°C. As for mass transfer, diffusion would result in wax buildup near the bottom of the tank. The diffusion coefficient for wax species (*n*-paraffins) in the solvent background of the fuel would be required for a mathematical description.

Convection currents can become the dominant factor for both heat and mass transfer, particularly under ullage conditions. Rayleigh-Benard convective instabilities in the form of cold fingers can develop, particularly at the upper surface of the fuel, resulting in altered mass- and heat-transport patterns. Velocities on the order of 1 cm/s have been observed in fingers, which reach 10–15 cm in length before breaking up. (These observations were made on the NASA Lewis simulator.) Gradually, a secondary flow (thermosiphon recirculation) develops, which reduces temperature gradients and may fluidize solid wax formations. However, the increased heat transfer will tend to aggravate the buildup problem by exposing much more of the fuel to subsolidification temperatures. One significant consequence of convection is the tendency to couple heat and mass transfer. Descriptions of both processes require viscosity data (which can depend significantly on temperature in the single and two-phase cases).[3] Viscous effects act in the momentum transfer equation (Navier-Stokes) for velocity profiles. Other information, such as that involved in the density difference drive of flow, is also required. In the extreme case, all the fuel in the tank solidifies.

Experimental Procedure

Some of the generic processes in operation during cooling can be illustrated by the following profiles in the experiment to follow, particularly temperature and mass (density) profiles. Most of the published cold studies were performed for the large semirectangular inboard wing tanks. As an alternative, we used a cylindrical tank to model outboard cylindrical (pod) tanks, which are found on some military fighter aircraft.

Figure 2a shows the dimensions of the pod tank model and the placement of thermocouples in it. Figure 2b shows the temperature profiles vs time for a prototype cooling experiment. More will be said about that experiment after a modification to reach realistically low temperatures much colder than in the prototype is described. Figure 2c shows a plastic shell that can be placed around the tank. It adds a little over an inch to the diameter. Coolants can be added through the slot in the shell (or baths of controlled temperature can be made in the shell itself). Dry ice and isopropanol easily drive the temperature well below −50°C, and insulation keeps the rate of CO_2 escape into the surrounding environment low.

The plan behind the prototype experiment was first to review the typical simulation study. The tanks were cooled by a prescribed temperature program. At some particular time (temperature condition), the tanks were drained and the "holdup" fraction of fuel in the tank determined. Typically, these data were correlated (although somewhat poorly) as increasing holdup vs colder temperatures.[2] Some results for our prototype experiment appear in Fig. 3 (model fuel holdup vs fuel temperature as it cooled in the room from 40°C). The review and our prototype experiment found scatter if holdup was correlated only to temperature.

The second point in our plan was based on the conjecture that the scatter could be better understood if conditions of the wax solids, as well as temperature, could be noted just before a drain event. Imaging techniques based on x rays, gamma rays, ultrasonics, and nuclear magnetic resonance all had the potential to inform on the wax state. However, instruments for these techniques commonly reside in clinical settings. Therefore, the prototype (simultaneous temperature and holdup) experiment had to be: 1) Realistic enough to relate to the prior simulation studies and to show the well-known scatter in holdup vs temperature; and 2) benign enough so that it could be run in the environment of the operational clinic.

The cooling system for the model tank had to be as simple as possible; natural convection at room temperature was

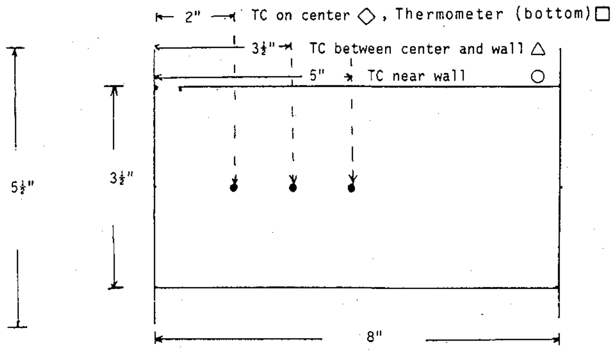


Fig. 2a Tank geometry including thermocouple locations.

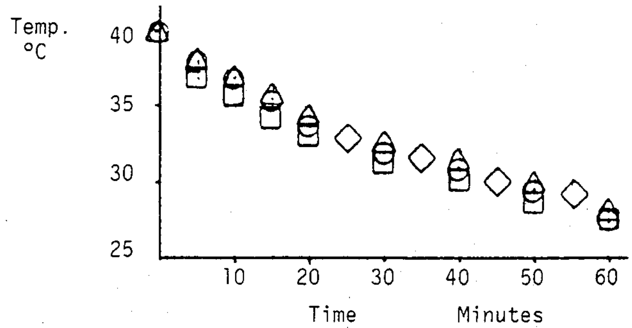


Fig. 2b Prototype experiment profiles in cooling from 40°C to room temperature.

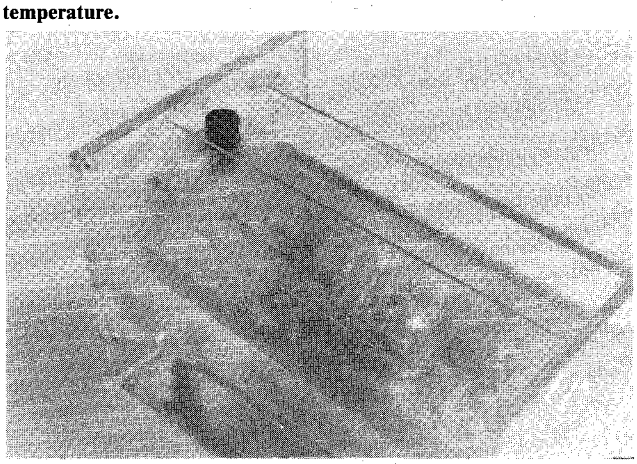


Fig. 2c Tank with cooling jacket.

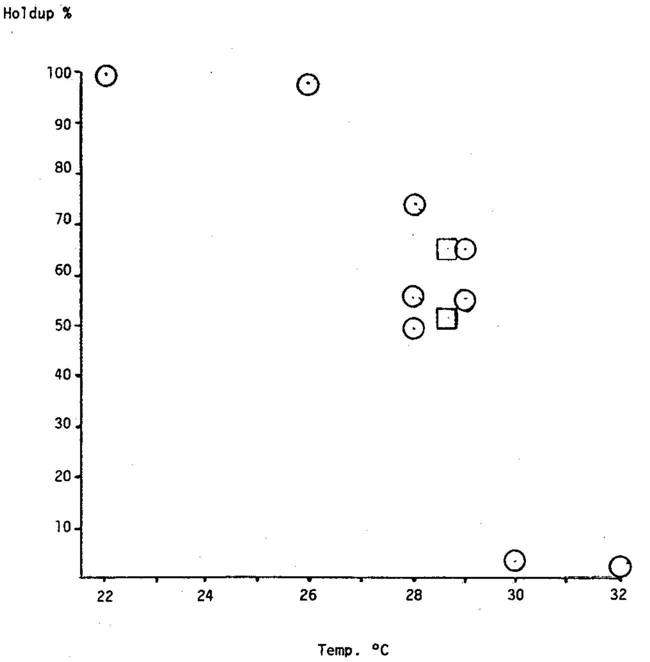


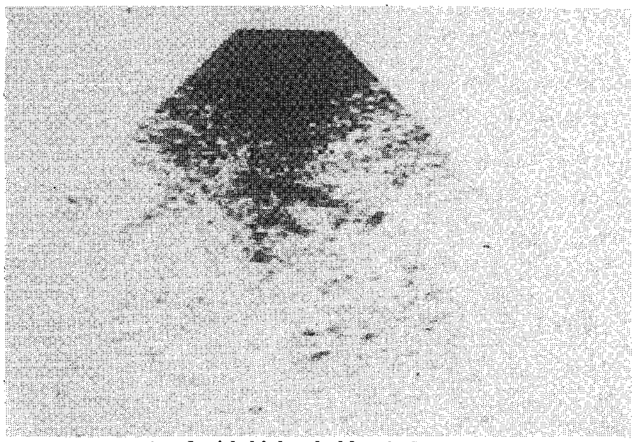
Fig. 3 Fuel holdup in a cold tank depends somewhat on temperature, with variation appearing in a transition zone. Symbols ○ and □ denote data corresponding to views in Fig. 4.

desired. In this way, the ultrasonic probe could be put on the outside surface of the tank without the complications of a cooling jacket.

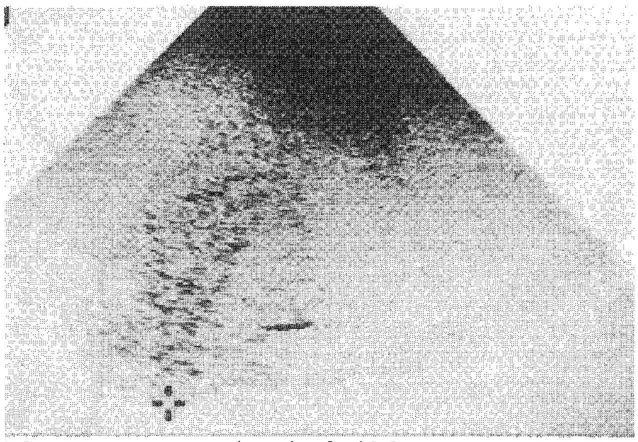
A fuel model of canning wax (substantially in paraffins; see GC analysis, Table 1) and hexane appeared safe to handle, in much the same way as petroleum-based products like mineral oil or alcohols. Thus, the model fuel was prepared by adding wax to hexane and warming it slowly to 40°C. It was then allowed to cool to room temperature to see if it would go through the phase transition. This heating and cooling cycle was repeated with incrementally more wax until the required transition was noted. The final recipe was 464.5 g of model fuel, 0.22 of which was wax. (Ullage appeared in the tank and, occasionally, slight amounts of hexane were added to maintain constant volume during the course of the experiments.)

The experimental procedure required the filled tank to be heated to 40°C by placing it in a furnace at that temperature. The tank was allowed to cool to the desired temperature, as indicated by the glass thermometer (thermocouples were not present when any of the holdup data were taken). At the desired temperature, the thermometer was removed, and a combination plug/glass tube heating coil drain assembly was inserted. The drain assembly was heated to about the fuel temperature, and then the tank with assembly was inverted to drain. Without heating, a cold (room-temperature) drain leg would plug. The glass tube and plug were flush with the tank bottom. Evidently, any material that would flow at all came out of the glass tube without restriction because when the plug and tube were removed (affording full port for flow, thus greatly reducing the restriction further), no additional flow was observed. The plug and tube were used to control the flow because the full port flow without them is massive and percolative, unlike realistic or simulator conditions. The drained wax was weighed, and the Fig. 3 data were produced.

To be sure, the Fig. 3 data had the well-known scatter in holdup vs temperature. Two of those points, however, were generated in the clinical setting, where the ultrasonic images shown in Fig. 4 were taken just before draining the tank. The purpose here was not to establish a correlation, but merely to show that differences in holdup at some temperature might be related to differences in wax structure. The coarser wax structure view (Fig. 4b) was typical of several associated with the indicated lower holdup at 28.6°C. The fine structure (Fig. 4a)



a) Associated with higher holdup in Fig. 3 at 28.6°C



b) Coarser wax structure (associated with lower holdup in Fig. 3 at 28.6°C); the cross hairs denote the opposite side of the tank

Fig. 4 Ultrasound images of fuel holdup in model tank at 28.6°C. The probe is about 30 deg from top dead center.

Table 1 Species distribution in the wax component of the model fuel

Carbon no. (*n*-paraffin)[a]	Weight, %
16	1.7
17	13.1
18	17.3
19	18.9
20	17.9
21	13.3
22	8.7
23	5.8
24	2.9
25	2.7
26	0.6

[a]From gas chromatography data.

was present in observations at the higher holdup. Of course, more data must be taken before those observations can be established. The point is that the possibility of that establishment has been demonstrated.

The prints in Fig. 4 were produced from x-ray type of emulsions. These emulsions were generated by the permanent record unit connected to an Acuson 128 ultrasonic imaging apparatus. The Acuson probes have several crystals that generate 128 information channels. These can be processed in a variety of ways, depending on the direct search by the operator for optimum conditions. Ultrasonic signals are either reflected, refracted, transmitted, or absorbed. The Acuson 128 has eight sliding potentiometers that help in part to selectively amplify reflected signals from different depths, potentially enhancing the image. Conditions for the two views in Fig. 4 were produced by about the same setting, even to the point of an attempted duplication of potentiometer settings.

Table 2 Dependence of diffusivity on thermal history; diffusion in liquid phase: $n-(28+32+36)+$ hexanes[a]

Thermal treatment	log D_H [cm^2/s]	log D_w
	±0.03	±0.03
Cool 63°C↔25°C	−4.54	−5.27
After 20 min	−4.53	−5.28
Cool 63°C↔0°C↔25°C	−4.64	−5.44
Quench 63°C↔25°C	−4.89	−5.92
Quench 63°C↔77K↔25°C	−4.85	−6.01
After 12 h	−4.87	−5.88

[a]30% [C_{28}(0.25) + C_{32}(0.50) + C_{36}(0.25)] (Bowax) + 70% hexanes; $T_c \approx 36$°C.

Figures 5a–d show the visual sequence in the prototype experiment. The clear conditions of the fuel at 37°C are the same as at 40°C. At 31°C, waxes as a white cloud are apparent. Somewhere between about 34 and 30°C, most of the fuel becomes cloudy.

The cloudiness is due to small crystals of wax forming. A gross mathematical description would require a term for the generation and growth of these particles, and then their subsequent motions would need to be followed. On the other hand, if conditions were held, as in Fig. 5b, at 31°C, wax buildup at the bottom might proceed via diffusion of wax species to the crystallizing front and subsequent addition to the front. This problem would be similar to classical problems dealing with moving fronts. A diffusion coefficient for the waxes (such as *n*-paraffin molecules) in hexane would be needed. Although other sources could suffice for that data, the spin echo technique of nuclear magnetic resonance is particularly effective at extracting this information.[4] This technique deals with spin alignment of nuclei as manifest in an echo. Conditions that serve to dephase the spin (attenuate the echo) can be adjusted so that the detection of relative motion of nuclei is enhanced. This relative motion of nuclei, and hence of the molecules of which they are a part, can be related to molecular Brownian motion and, hence, to diffusion.

Figure 6 shows a plot of echo attenuation vs a field gradient parameter for the model fuel at 26°C (field parameter detail not crucial here; for details, see Ref. 4). This plot can be decomposed into a weighted sum of two distinct sources, hexanes and waxes. The diffusion coefficient of each are, respectively, log $D_s = -4.96$ and log $D_w = -5.35$.

The 26°C state would be significantly below the cloud point, and solid structures would be present. To determine if such structures interfered with molecular wax species diffusion, the time scale in determining the diffusion coefficient was adjusted. If wax molecules were being restricted in their random walk, a longer time scale should have revealed this, because the molecules would then be more likely to encounter a solid barrier of crystallized particles of wax. No such dependence was found, so that the wax molecules evidently walk right through, or past, what visibly appear to be solid wax structures. The analogy to a classical freezing front (for example, ice forming in water) does not apply.

If the temperature dependence of the diffusion coefficient reflects the tendency to crystallization phase change, then adjustments that affect crystallization should also affect the diffusion coefficient. It is known that the rate of cooling of waxy fuels affects the crystal morphology (hence, crystallization kinetics, although the arguments could perhaps be more com-

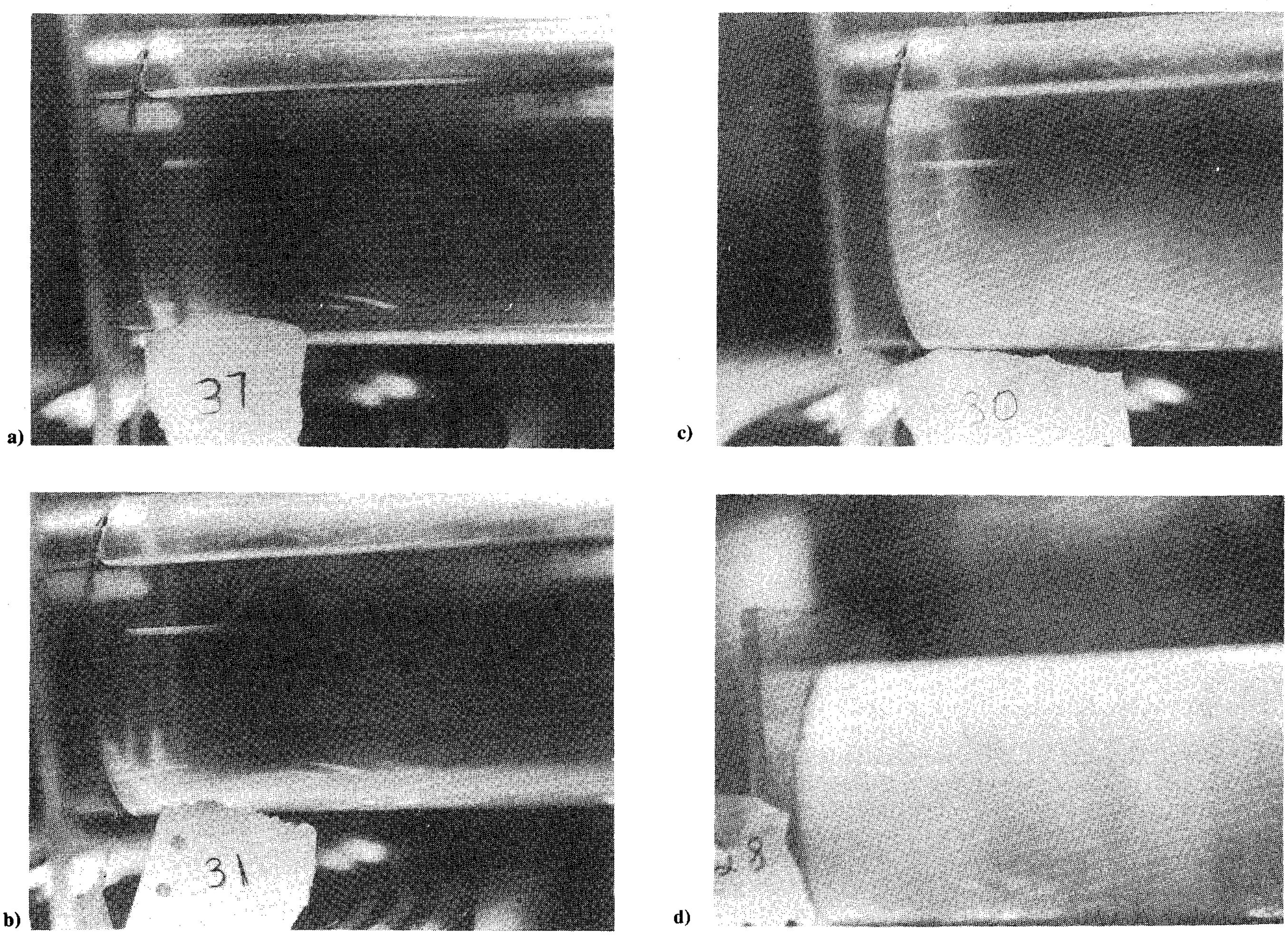


Fig. 5 Clouding effect at successively lower temperatures.

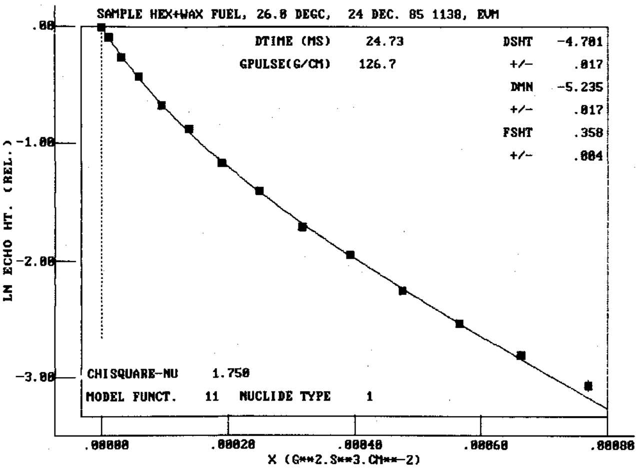


Fig. 6 Spin echo attenuation as a function of field parameters reflects species motion and, hence, self-diffusion.

plete). Not surprisingly then, Table 2 shows that a quench and slow cool lead to different diffusion coefficients. Diffusivity dependence on cooling rate further implicates the crystallization process as a cause of variation with temperature, not solids, encounters.

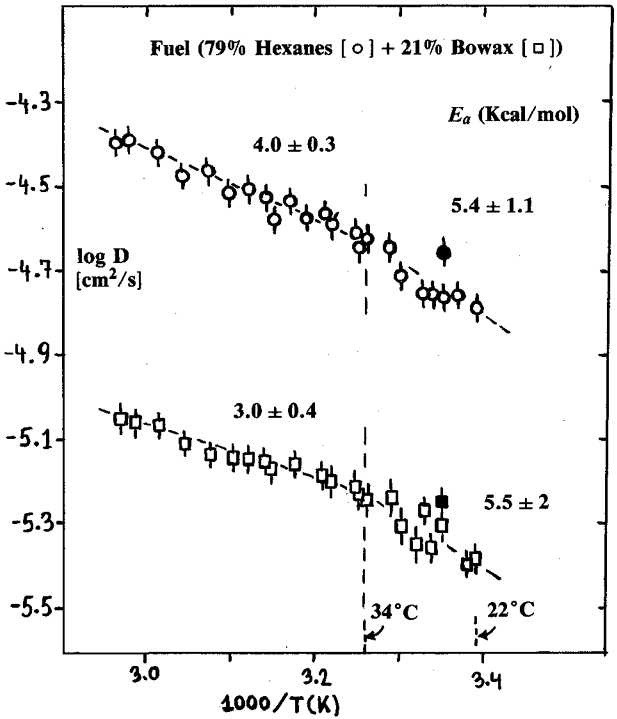


Fig. 7 Diffusion coefficient as a function of temperature.

Summary

In summary, the views offered here are radically different from classical "freezing front" problems, which might be projected from casual observations of wax solids building up on, for example, the tank bottom. Another major contribution has been to show the possibilities for in-situ wax visualization.

References

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