VEGETATION DAMAGE, FUEL DROPLET DISTRIBUTION AND AIRPLANE HEIGHT

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Abstract

The satellite imagery taken on June 25th, 2010, about two months after the crash of the Polish TU-154M, tail number P101, near Smolensk, Russia, show three distinct areas of vegetation damage east of the runway 26. All the areas are about 40m to 50m wide and up to 170m long – stretched in the downwind direction from the calculated positions of the airplane corresponding to the reported three airplane damages. The first damage was the loss of the left wing tip, then, about 1.6s later, followed a damage of the central part of the left wing, and 1s after that followed a damage of the central wing tanks, which took place shortly before the false detection of an "airplane landed" event (TAWS 38). In this study a fuel droplet distribution for the possible release of fuel is estimated based on experimental and theoretical results reported in the past by a number of researchers investigating jettison of jet fuels. The resulting ground contamination profile is then determined based on this droplet distribution profile and is compared to the zones of vegetation damage for two cases of low and high trajectories: the case of a low trajectory of 15m above local ground, and a case of a high trajectory of 45m above local ground. The observed vegetation damage correlates well with the calculated contamination profile of the high trajectory, while it is not tenable within the frame of the low trajectory. The latter scenario would demand droplet sizes produced at airplane speeds at least 2 times higher than the TU-154M flew during the said jettison process in Smolensk. The resulting ground contamination levels estimated in this work suggest that the third zone of damaged vegetation is likely to be produced by an amount of fuel of about 9-10 ton, equal to the amount carried by the central fuel tanks. The bottom skin covering the central fuel tanks is missing on the official photo showing the gathering of the wreckage after the crash. Parts from the plane were found in the ground about 100m before the crash site near the Kutuzov Street at the location where such parts released from the plane during the third jettison of fuel are expected to make their ground contact.

***Keywords** - jet fuel A1 droplet distribution, jettison, wing damage, Smolensk, TU-154, high trajectory.*

Streszczenie

Na zdjęciach satelitarnych z dnia 25 czerwca 2010 r, około dwóch miesięcy po katastrofie polskiego TU -154M z numerem P101, w Smoleńsku na wschód od pasa startowego 26 można zaobserwować trzy wyraźne obszary uszkodzenia roślinności. Każdy z tych trzech obszarów tworzy wąską strefę o szerokości 40 do 50 m i długości 170 m rozciągając się w kierunku wiatru od obliczonej pozycji raportowanych wcześniej uszkodzeń samolotu –- najpierw utrata końcówki skrzydła, potem około 1.6 s później uszkodzenie centralnej części lewego skrzydła i znów około 1s późniejsze uszkodzenie skrzydłowego zbiornika tuż przed fałszywym sygnałem "samolot ląduje" (TAWS 38). W niniejszej pracy oszacowano dystrybucję kropel paliwa dla możliwego uwolnienia paliwa. Podstawą do obliczeń są wyniki eksperymentalnych i teoretycznych badań przeprowadzonych przez kilku badaczy na temat rozproszenia paliwa zrzucanego przez samoloty. Znaleziony na tej podstawie kontur obszaru zanieczyszczenia na powierzchni ziemi został porównany ze strefami uszkodzenia roślinności w Smoleńsku dla przypadku niskiej trajektorii - 15 m powyżej gruntu i wysokiej trajektorii - 45 m powyżej gruntu. Zaobserwowane uszkodzenia roślinności z wielką dokładnością pokrywają się z obliczony obszarem zanieczyszczenia odpowiadającym wysokiej trajektorii i nie mogą być wyjaśnione dla przypadku niskiej trajektorii. Ten drugi przypadek wymagałby takiej wielkości kropelek, jakie powstają przy prędkości samolotu, co najemnej 2 razy większej niż prędkość, niż prędkość jaką miał w Smoleńsku TU-154 M podczas procesu zrzucania paliwa. Wynikające poziomy zanieczyszczenia ziemi oszacowane w tej pracy sugerują, że trzecia strefa uszkodzonej roślinności jest spowodowana przez ilość paliwa z około 9-10 tony, która równa się ilości zawartej w centralnych zbiornikach paliwa. Dolne poszycie pokrywające centralne zbiorniki paliwa jest pomijane na oficjalnych zdjęciach pokazujących zebranie szczątków wraku po katastrofie. Części samolotu zostały znalezione w ziemi około 100m przed miejscem katastrofy blisko ulicy Kutuzowa w miejscu, gdzie takie części odpadły od samolotu, podczas gdy trzeci wyrzut paliwa dosięgałby powierzchni ziemi.

***Słowa kluczowe** – rozrzut kropel paliwa A1 odrzutowców, zrzut paliwa z samolotu, uszkodzenie skrzydła, TU-154, wysoka trajektoria.*

1. INTRODUCTION

While there is a fair amount of information in the literature discussing vegetation damages caused by crude oil spills, there has been very little work done on using satellite imagery for identification and assessment of vegetation damages caused by the jetfuel contamination. For this reason [1] discusses the needs for use of other multidisciplinary tools for such investigations and for analysis of the extent of damages and their predictions of potential future impacts. Reaching out to other disciplines is especially recommended in the investigations of the sources of pollutions when they are not readily identifiable.

Airborne military and civilian aircraft must occasionally jettison unburned aviation fuel into the atmosphere [2]. This has therefore been investigated and characterized over the past several decades. As early as 1959, Lowell developed a computer model to investigate the fate of jettisoned fuel [3, 4, 5]. In the 1970's, the United States Air Force (USAF) began comprehensive research into the fate of jettisoned fuel, culminating in a series of technical reports by Clewell. In addition to investigating the frequency and nature of fuel jettison events within the Air Force [6, 7] Clewell also investigated the evaporation and dispersion of JP-4 with a

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computer model [8]. Clewell used Lowell's work as a foundation but incorporated more detail in the chemical model of JP-4 and in the simulation physics. Clewell extended his own work with JP-4 by using the same model code to investigate the less volatile JP-8 [9]. This research investigates the fate of the jettisoned fuel from initial release to final ground fall by numerically modeling the main physical phenomena governing the fate of this fuel: evaporation and advection. Using previous work in evaporation, dispersion and free fall of fuel droplets as a foundation, this work presents a simple evaporation and advection model that produces very similar results as the more advanced evaporation, advection and dispersion models for case of the low altitude jettison of low volatile JP-8 or A-1 type fuel. In the particular case investigated in this work the ground temperature was close to 0°C, and the jettison occured at a very low height (less than 70 m above local ground). Therefore, the evaporation effect was playing only a minor role, which can be illustrated by the estimated mass loss of droplets of diameter D=200 μm is less than 5% during their free air travel. Thus the advanced evaporation models taking the dependency of evaporation with respect to the temperature profile of each individual droplet into account can be simplified.

2. MODEL

2.1. Plume Composition.

Jet fuel is a very complex mixture of hydrocarbons and to characterize the evaporating substance perfectly is not practical. Furthermore, variations in the refining process result in variations in the composition of the fuel [10]. The more volatile fuel components will evaporate faster than the less volatile components. As the mixture evaporates, the less volatile components increase in concentration, changing the fuel properties. The work presented here is limited to the case of jettison at near ground temperature close to 0°C with a low ambient advection velocity for the low volatile jet fuel. Therefore, the overall evaporation plays a minor effect, and the fuel is characterized by bulk "soup" parameters rather than by a sum of parameters connected to the mixture of a finite number of species that approximate the physical behavior of the compounds in the actual mixture. The bulk evaporation constant is found in this work as to give good agreement between the results reported by [1] for the case of ground temperature of 0°C , low volatile fuel and jettison altitude of 1500 m and the result found in this work for the same.

2.2. Droplet Size Distribution

The droplet size distribution produced during the fuel jettison will depend strongly on the conditions of the jettison. Fig. 1 shows the distribution obtained with an airplane velocity of 175 m/s, and Fig. 2 shows the same obtained in a different experiment with an airplane velocity of 120 m/s. The red curve in Fig. 1 is found by adjusting Clewell's data for the differences in airspeed in comparison with the investigated case by the factor χ = 175/75 = 2.33. Since the effect of the actual much higher jettison rates in this study is not corrected for, the set of curves should be regarded as defining minimum levels. In reality the droplet distribution is expected to be shifted further towards larger droplets. Note for the airplane velocity of 75 m/s the percentage of the entire mass below D = 200 μm is calculated as P(D ≤ 200 μm) = 2% and the percentage P (D ≤ 82 μm) < 0.08%. The amount of fuel between D = 200 μm and D = 270 μm is about 3.1% and the remaining about 95% fuel will have a droplet size larger than D = 270 μm. As shown below, this fuel is expected to travel a distance of 120 m or shorter when released at 45 m height, which correlates well to the darkened area of zone 3 in Fig. 4.

The black curves of Fig. 2 are original theoretical and experimental data obtained with a low flying Buccaneer and jettison rate of 7.5 kg/s. The blue curve is found by adjusting the Cross Picknett data for the differences in airspeed in comparison with the investigated case by the factor χ = 120/75 = 1.6. As mentioned earlier, since the effect of the actual much higher jettison rate is not corrected for, the set of curves should be regarded as minimum curves. In reality the droplet distribution is expected to be shifted further towards larger droplets. Note for the airplane velocity of 75m/s the percentage of the entire mass below D=200μm is found as P(D ≤ 200 μm) =1% and the percentage P(D ≤ 82 μm) less than 0.1%. The amount of fuel between D=200 μm and D=270 μm is about 4% and the remaining about 95% fuel will have a droplet size larger than D = 270 μm. As shown below this fuel is expected to travel a distance of 105 m or shorter, which correlates well with the darkened area of zone 3 in Fig. 4. From this figure one can observe the distinct and significant damage of vegetation in the three areas (zone 1, zone 2 and zone 3) circled by the dashed lines. Adding the recorded vertical acceleration signal by the Polish QAR (black line) and the wind direction of 120° (yellow arrow) show evident agreement in directions of all the three distinct areas of vegetation damage to the approximate positions of the loss of the wing tip, loss of additional wing area and the third event emptying the center fuel tanks prior to triggering the TAWS 38 recording. The calculated vertical acceleration (red line of inserted bottom figure shows same characteristic decline as the recorded signal. Note the severe darkened area of zone 3 within a distance of 105m from the trajectory. As shown below this predicts the majority of the fuel droplets have a size of D = 270 μm or larger. This correlates well with Fig. 1, where it can be seen that about 95% of the droplets are expected to have a diameter larger than D = 270 μm. The length of zone 3 is approximately 170 m and the width approximately 40m at the beginning. This indicates the fuel of zone 3 was released in less than 0.4 s.

The initial aircraft velocity (and thereby fuel velocity) has a strong influence on the size of the droplets formed. The higher is the aircraft velocity the smaller will be the produced droplets. The effect of airspeed on the formation of sprays has been studied intensively for various commercial reasons. Roughly the characteristic diameter (for instance measured by Sauter Mean Diameter or other characteristic diameter) will be inversely proportional to the speed of the air forcing the atomization process [11]. Based on the experimental and theoretical data shown in Fig. 1 and Fig. 2 the droplet distribution for the case investigated in this work (V = 75 m/s) can be estimated from both sets of data. The results are shown in the Fig. 1 and Fig. 2, and data are summarized in Tab. 1. This predicts between 3.1% to 8.5% of the jettisoned fuel will have a diameter between 200μm and 270 μm. Both sets of data are shown in Fig. 3 together with their respective fitted curves.

Tab. 1. Summary of droplet size distribution data based on two different sets of experimental data.

Data Set	Airplane	Jettison Rate	Jettison Height	Airplane Speed at Jettison	Velocity Factor V	CALCULATED FOR V=75m/s			
		Q [Kg/s]	H [m]	V_{exp} [m/s]	$V_{exp}/V_{tu\text{-}154M}$ [1]	Mass with D<82 µm	Mass with D<200 µm	Mass with D>200 µm and D<270 µm	Mass with D>270 µm
Clewell	KC-135	56	1500	175	2.33	<0.08%	2.0%	3.1%	95%
Cross &Picknett	Buccaneer	7.5	15	120	1.60	<0.03%	4.2%	8.5%	87%

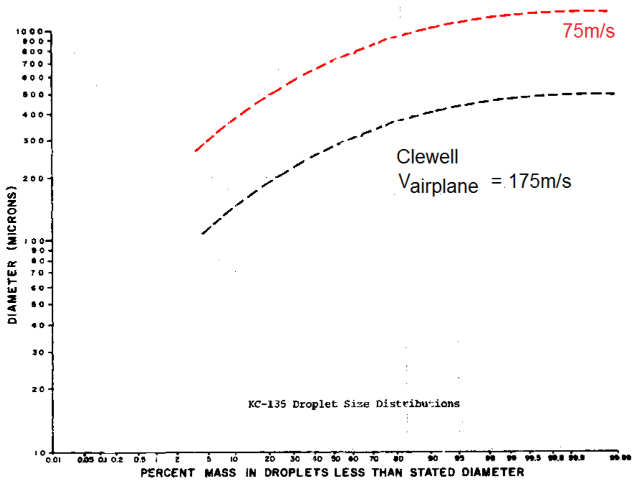

Fig. 1. Modified figure taken from [8]. Experimental data based on a jettison with a KC-135 aircraft with an airspeed of 175 m/s and a jettison rate of 330 g/m or 56 kg/s.

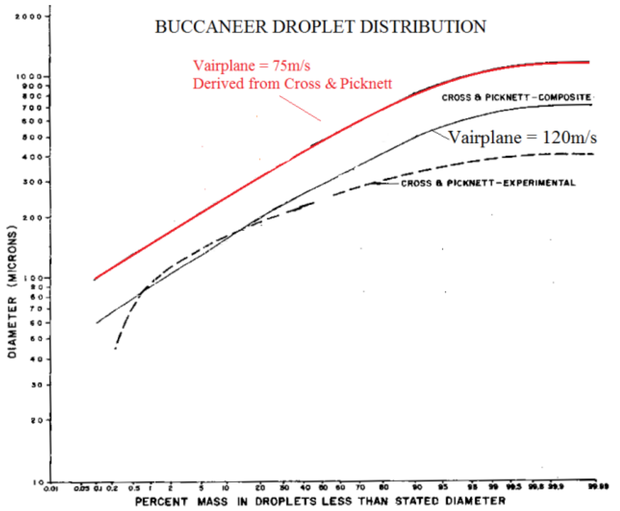

Fig. 2. Modified figure taken from [8]. Experimental data based on a jettison with a Buccaneer aircraft with an airspeed of 120 m/s and a jettison rate of 7.5 kg/s.

The jettison rate is also an important aspect. Large jettison rates tend to produce larger droplet diameters as the air might not possess sufficient energy to thoroughly atomize all of the fuel [8]. The fluid slows down while breaking up, so the efficient airspeed for further breaking of the droplets, from medium size to smaller size, decreases over time from the moment of the initial release until the fluid velocity equals that of the ambient air. Judging based on the widths of the damaged vegetation zones, in the case examined here, the release of fuel occurred at a rate that far exceed the rates studied in the referenced work; and therefore, the droplet distribution found in this work is most likely underestimating the actual sizes in reality. Correcting for this effect will only enhance the conclusions found in this work.

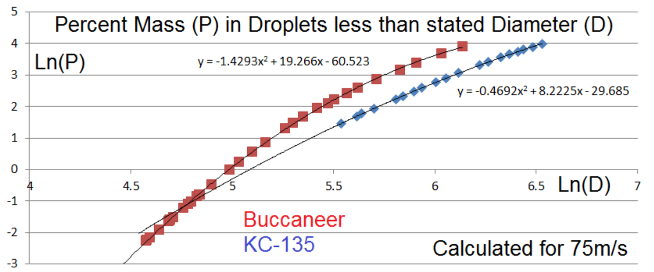

Fig. 3. Data from Fig. 1 and Fig. 2 based on the two different jettison experiments and both calculated for an airplane speed of Vairplane = 75m/s. The figure shows ln(P) as a function of ln(*D*) for *P* < 50%, where *P* is the percentage mass in droplets less than stated droplet diameter *D* in µm. The second order polynomial curve fits are shown as lines, and the respective coefficients are listed for each curve.

2.3. Wake Effects

Clewell [8] neglected wake effects in the free fall, and in his evaporation model mentioned that this underestimates initial droplet velocities; the wake tends to push the plume down when the plane is flying in a normal horizontal mode. For fuel jettisoned near or from the wing tip during the third release where the plane left roll is assumed to be nearly 90° [12] the wake effect could tend to send some of the fuel even upstream to the wind direction, and can add to explain why the vegetation damage of this third zone starts further to the south (or more to the left) than the two other zones where the plane roll was insignificant.

2.4. Model Assumptions

The following assumptions are made:

- Spherical symmetric droplets.
- Quasi-steady state evaporation. The droplet diameter is fixed at each time step and then updated after the new mass and velocity are calculated.
- Evaporated mass is proportional to the droplet surface area.
- The evaporation constant does not vary throughout the time the droplet is airborne.
- Each droplet evaporates independently of the rest of the plume.

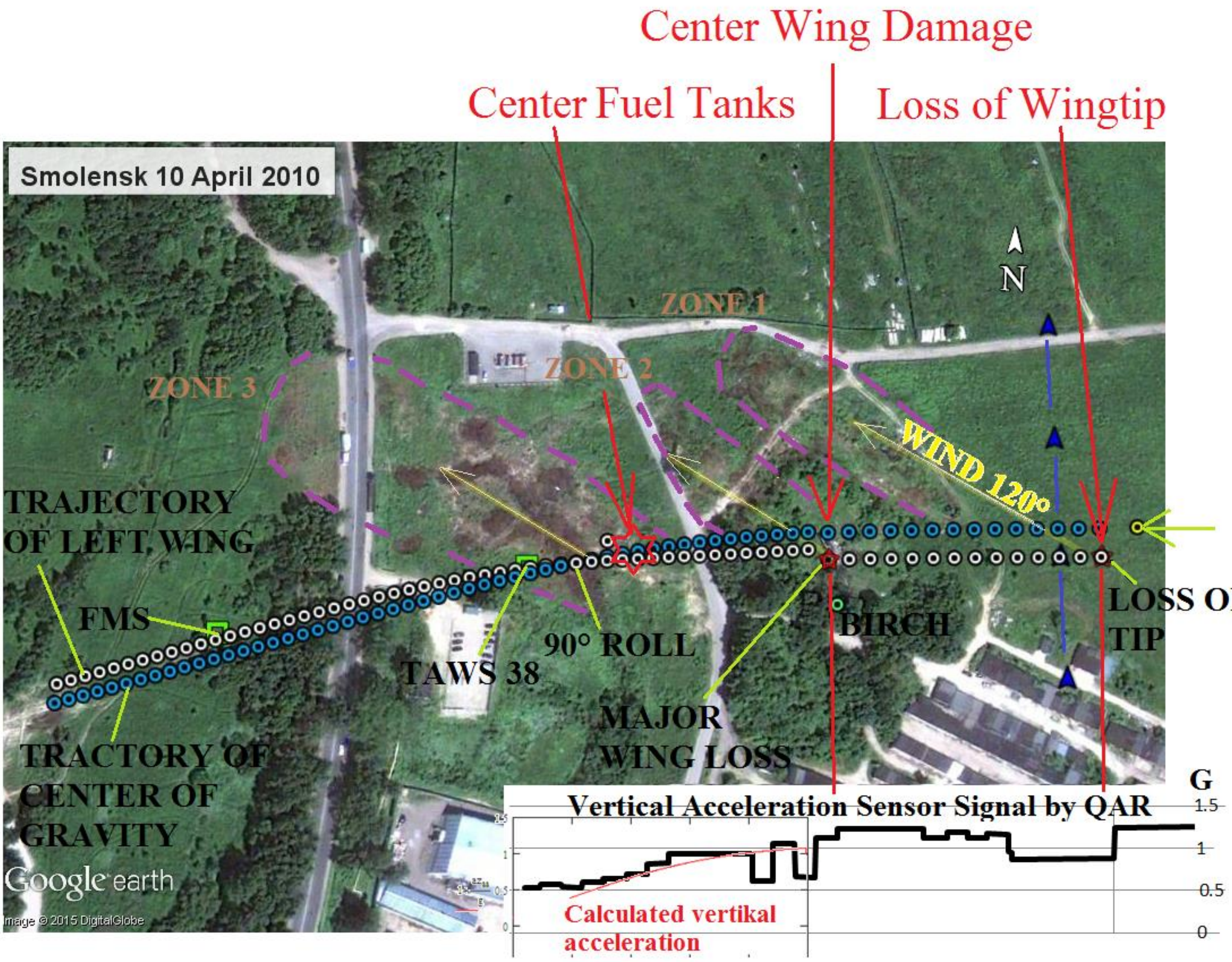

Fig. 4. This is taken from [12]. The calculated trajectory for the center of gravity (blue) and the left wing tip (white). The satellite picture is from the 25th of June 2010 (about two months after the crash.

- Each droplet falls independently. The entrainment of smaller drops by larger, and faster, drops is ignored. Lowell noted that this assumption would result in terminal velocities that were initially too low [4]. Also growth and decay by collision is ignored.
- The initial surface temperature *of each droplet* is equilibrated with the ambient air temperature. Note: The fuel was most likely colder than the ambient air temperature close to the ground as the plane was descending from a large altitude with lower temperatures. As evaporation in the examined case only plays a negligible role, modelling the precise temperature becomes less important with respect to the overall results. Colder initial temperatures reduce the rate of the initial evaporation.
- No wake effect is included.
- The Langmuir-Blodgett relation between the droplet drag coefficient, C_d, and Reynolds Number Re, exists [2].
- As the direction of the wind of the examined case is nearly perpendicular to the direction of flight the initial velocity of the droplets after their formation (at $t = 0$) is assumed equal to the wind velocity U.
- The ambient wind speed is modelled using a logarithmic velocity profile of a turbulent fluid flow near a boundary with a no-slip condition [13],[14].
- The initial vertical droplet velocity $V_z = 0$ at $t = 0$.
- Wind direction is 110° - 130° and independent of height. The wind speed at the standard measurement height ($Z = 10$ m) is $U = 2$ m/s [15:48].

2.5. Model Equations

$$m\frac{dV}{dt} = F\,, \tag{1}$$

Where m is the droplet mass, $dV/dt = a$ net acceleration of the droplet, t is the time variable and F the net force acting on the droplet. Assuming the net force F on the droplet is identical to the gravitational force minus the drag force. The drag force on an immersed body can be calculated by [16:360]

$$Drag = C_d A \rho \frac{V_{rel}^2}{2} \tag{2}$$

Where A is the projected surface area in the flow, ρ is the density of the fluid (in this case the air density ρ = 1.272 kg/m^3) and V_{rel} is the velocity of the droplet relative to the free stream air flow. As the droplet velocity after its formation (at $t = 0$) is assumed equal to the free air stream velocity, U, then $V_{rel} = V_z$ where V_z is the vertical velocity towards the ground.

The droplet drag coefficient is a function of the Reynolds number Re of the flow; the Reynolds number is a dimensionless ratio of inertia force to friction force, usually expressed as [16:200]

$$\mathrm{Re} = \rho \frac{V_{rel}^2 D}{\mu} \tag{3}$$

Where D is the droplet diameter and μ is the kinematic viscosity of the fluid ($\mu_{air}(0°C) = 1.618*10^{-5}$Pa*s).

Bilanin [17] and Teske [18] suggest a relationship between Re and C_d for spherical droplets, originally developed by Langmuir and Blodgett

$$C_d = \frac{24}{\mathrm{Re}}(1 + 0.197 * \mathrm{Re}^{0.63} + 2.6 * 10^{-4} * \mathrm{Re}^{1.38}) \tag{4}$$

When evaluating the droplet state at a number of discrete times separated by a small time increment one gets:

$$t_i = t_{i-1} + dt \tag{5}$$

Where

$$dt = \frac{\Delta T}{N}. \tag{6}$$

And N is a chosen large number (N = 200.000) and ΔT is the time it takes for the droplet of a given size to reach the ground. From the length of the zone of the damaged vegetation measured in the direction of the wind and the average wind speed U = 2 m/s one can find the largest duration (airborne time of the smallest droplets) as approximately

$$\Delta T = \frac{L}{U} = \frac{170 * m}{2m/s} = 85s \tag{7}$$

From one time step, t_i, to the next time step, t_{i+1} the net acceleration is found by (1) as

$$a_i = \frac{F_i}{m_i} = g - \frac{Drag_i}{m_i}. \tag{8}$$

The vertical velocity, v, can then be found as

$$v_i = v_{i-1} + a_i * dt \tag{9}$$

And the travelled distance z in the vertical direction as

$$z_i = z_{i-1} + v_i * dt \tag{10}$$

Assuming the evaporation of mass is proportional to the surface area of the droplet, the mass can be found as

$$m_i = m_{i-1} - s_i * k * dt \tag{11}$$

Where the evaporation constant, $k = 0.022*10^{-6}$ m/s gives good agreement between the results of [2] and this work (see Fig. 11). Finally the surface area, s, of a spherical droplet and the projected surface area, A, can be found as

$$s_i = \pi D_i^2 \tag{12}$$

$$A_i = \frac{\pi}{4} D_i^2 \tag{13}$$

Assuming the droplet is a sphere, the droplet mass can be found as

$$m_i = \frac{\pi}{6} D_i^3 \rho_d \tag{14}$$

Where the density of the jet fuel is $\rho_d = 809$ kg/m^3.

In order to evaluate how rapidly droplets of a given size will decelerate from their initial airplane velocity to the speed of the free airflow, this is studied separately neglecting the evaporation of the droplets during this deceleration (and breakup process). Substituting expressions for drag force (2) and mass (14) in equation (1) yields the differential equation

$$\frac{dV}{dt} = \frac{-3\rho}{4\rho_d D} C_d (U - V)^2 \tag{15}$$

Where the minus sign arises from the drag force always acting towards the direction of motion. As the initial droplet velocity is nearly perpendicular to the free airstream velocity, U, the case of deceleration is simplified to one dimension in the direction of the flight ($U = 0$).

Assuming the droplet has the initial airspeed V_0 at time $t = 0$ one gets

$$\int_{V_0}^{V} \frac{1}{V^2} dV = \int_0^t \frac{-3\rho}{4\rho_d D} C_d dt \tag{16}$$

Integration of both sides neglecting the fact that C_d changes during the deceleration time reveals

$$V = \frac{V_0}{1 + V_0 * \frac{3\rho}{4\rho_d D} C_d t} \tag{17}$$

Thus the velocity can be found as a function of time and assuming ρ, ρ_d and D constant during the deceleration process one gets

$$V_i = \frac{V_0}{1 + V_0 * \frac{3\rho}{4\rho_d D} C_{d\,i} t_i} \tag{18}$$

Where C_d is a function of the Reynolds number, which again is a function of velocity.

The wind near the ground will be strongly influenced by boundary layer effects and the wind velocity as a function of height , $U(z)$ at time step i, can be approximated [13], [14] as

$$U_i(z_i) = \frac{U_0}{k} \ln(\frac{z_i}{z_0}) \ , \tag{19}$$

where U_0 is found

$$U_0(z_0) = \frac{2m/s * k}{\ln(\frac{10m}{z_0})} \ . \tag{20}$$

Such $U_i(z = 10\text{ m}) = 2$ m/s, k is the von Kármán constant k = 0.40 [19], [20], [21] and z_0 is the average roughness length. Fig. 5 shows the resulting velocity profiles for three different values of z_0.

Here x is a typical upwind obstacle distance and H is the height of the corresponding major obstacles. For more detailed and updated terrain class descriptions see Davenport et al [22].

In this work the average velocity from z = 0 m to z = 15 m for a given average roughness length z_0 is noted as $U_{low}(z_0)$ and the average velocity from z = 0 m to z = 45 m is denoted as $U_{high}(z_0)$, i.e.

$$U_{low}(z_0) = \frac{\int_{z \to 0m}^{z=15m} \frac{U_0}{k} \ln(\frac{z_i}{z_0}) dz}{15m} \ , \tag{21}$$

$$U_{high}(z_0) = \frac{\int_{z \to 0m}^{z=45m} \frac{U_0}{k} \ln(\frac{z_i}{z_0}) dz}{45m} \ . \tag{22}$$

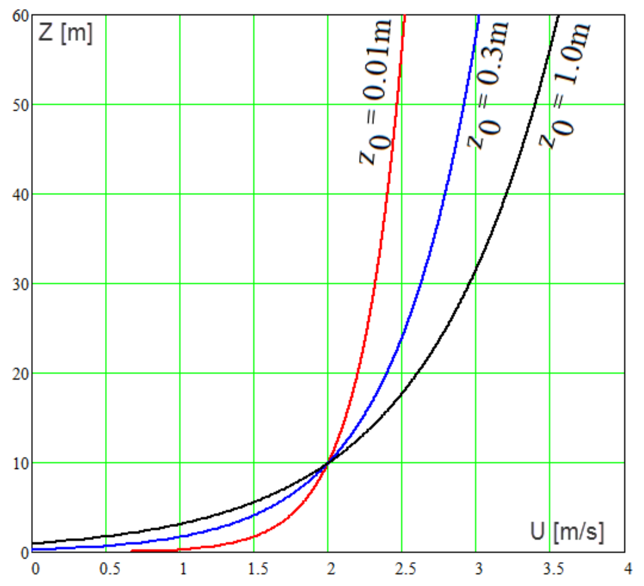

Fig. 5. The velocity profile for z_0 = 0.01 m, z_0 = 0.3 m, and z_0 = 1m.

And the ratio $\beta(z_0) = U_{low}(z_0)/U_{high}(z_0)$ is found to be a weak function of z_0 , as can be seen in Fig. 6.

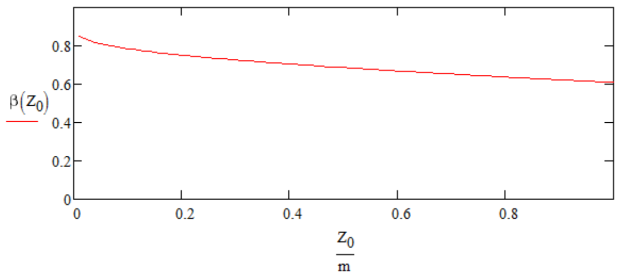

Fig. 6. The ratio $\beta = U_{low}/U_{high}$ as a function of the average roughness length for a wide range of values.

U_{low} is the average velocity from ground to 15 m height and U_{high} is the average velocity from ground to 45 m height. For a roughness value of z_0 = 1 m, $\beta \approx 0.6$ and for z_0 = 0.3 m, $\beta \approx 0.7$. This means the average speed of the lowest 0 m to 15 m is about 30% to 40% lower than the average wind speed of the 0 m to 50 m region, because the droplets need to be even smaller for the case of an initial jettison height of 15 m taking this effect into account, than if assuming equal average velocities for the two regions (no boundary effect). The stronger the boundary effect, i.e. the larger the z_0 value, the smaller the initial droplet size needs to be in order to create damage zones of vegetation as can be observed weeks after the crash. The smaller the droplet needs to be, the larger the airplane speed must be when creating the plume.

The travelled distance measured in the horizontal plane in the direction of the wind is found as:

$$X_i = X_{i-1} + U_i dt \qquad (23)$$

2.6. Solving the Equations for the free air travel

For each droplet size the initial boundary conditions are set up for the variables on the left hand side of the equations (9) through (13) for $i = 0$ ($t_0 = 0$), and for each small increment in time the new state is calculated using equations (3), (4), (5), (8) - (13) and (19) - (23). The time of travel of the droplet ΔT is found as the time t_x where the droplet reaches the ground. This is done for z_0 є [0.3 m; 1 m] and the travelled distance only depends weakly on z_0 (all are within ±17m), in agreement with Fig. 6. (The conservative value z_0 = 0.3 m is used for generating the plots presented in this work, see Tab. 2).

Tab. 2. Terrain classification from Davenport (1960) [23] adapted by Wieringa (1980) [24] in terms of aerodynamic roughness length z_0. The particular area of interest east of runway 26 at Smolensk Airfield is estimated to belong to class 4 to 7. A conservative value of z_0 = 0.3 m is used for generating the characteristic plots shown in the following chapter

Class	Short terrain description	z_0 (m)
1	Open sea, fetch at least 5 km	0.0002
2	Mud flats, snow; no vegetation, no obstacles	0.005
3	Open flat terrain; grass, few isolated obstacles	0.03
4	Low crops; occasional large obstacles, x/H > 20	0.10
5	High crops; scattered obstacles, 15 < x/H < 20	0.25
6	Parkland, bushes; numerous obstacles, x/H ≈ 10	0.5
7	Regular large obstacle coverage (suburb, forest)	1.0
8	City center with high- and low-rise buildings	≥ 2

2.7. Solving the Equations for the deceleration travel

In order to include the effect of the changing drag coefficient, the deceleration interval is divided into a large number of semi-stationary time steps. Within each time step the C_d can be regarded constant, and at the end the new C_d value is found based on the exit conditions of the prior time step. If the relative change in C_d from one time step to the next is larger than 1% the time step is halved. For each droplet size the initial boundary conditions are set up for the droplet velocity equal to the airplane velocity, the Re number and C_d number are found for $i = 0$ ($t_0 = 0$), and for each small increment in time the new velocity is found using equation (18) and new Re and C_d values are calculated using equation (3) and (4). The time of travel of the droplet ΔT is found as the time t_x where the droplet reaches a velocity of V_{end} = 0.1 m/s, and the travelled distance is found by summing the contributions $S = \Sigma V_i dt_i$ from $t = 0$ to $t = t_x$.

3. Results

3.1. The Deceleration Distance of the Droplet

The deceleration distance as a function of initial droplet diameter is shown in Fig. 7. The approximate position of the jettison can be estimated from the knowledge of the distance required to decelerate the largest droplets (see Fig. 8). Assuming droplets of D = 2500 μm to D = 3000μm as a result of an incomplete jettison process due to the low height and extreme jettison rates, the travelled distance of these will be about 25m. The presence of such large diameters also explains why the vegetation is damaged south of the trajectory (upstream to the wind) (see Fig. 8).

3.2. The Free Air Travel of the Droplet

Fig. 12a shows the droplet height as a function of travelled horizontal distance. The initial height of droplets of D_0 = 82 μm is H =15 m and the initial height of droplets of D_0 = 200 μm is H = 45 m. The remaining mass as a function of time for droplets of D_0 = 82 μm and D_0 = 200 μm is shown in Fig. 12b. The relative mass loss is higher for the small diameter due to the higher surface to volume ratio of the small droplet compared to the large droplet. Fig. 12c shows the horizontal velocity for droplets of D_0 = 82 µm and D_0 = 200 µm as a function of travelled horizontal distance. Fig. 12d shows the vertical velocity for droplets of D_0 = 82 µm and D_0 = 200 µm as a function of travelled horizontal distance, and as the evaporation only plays a minor role, the velocities are nearly constant.

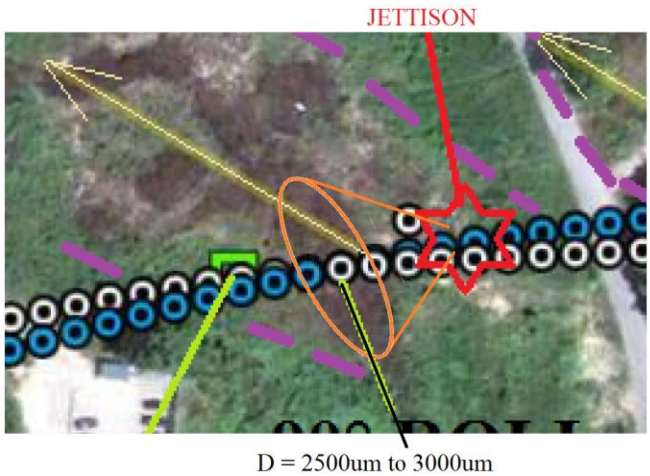

Fig. 7. The region inside the orange ellipse seems to be hit by the largest droplets travelling about 20 m to 30 m in the horizontal direction. The yellow arrow shows the direction of the wind.

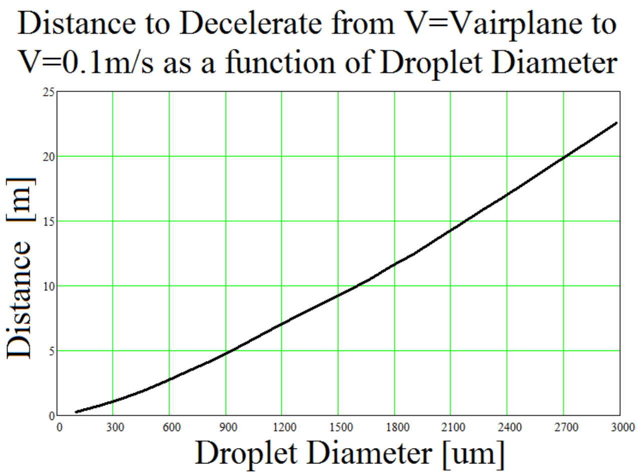

Fig. 8. The calculated distance required to decelerate from the initial speed of the airplane to 0.1 m/s as a function of droplet size neglecting evaporation.

3.3. Estimation of the Evaporation Constant, k

Based on the results published in [2] (see Fig. 11) the evaporation constant is found as k = 0.022*10^{-6} m/s. Note this value is not critical for the obtained results. Even a doubling of the value will only change the overall results insignificantly.

3.4. Estimation of the droplet size at the furthest boundary

The boundary of the vegetation zone furthest away from the place of jettison is assumed related to the limit, where the resulting contamination is passing some critical threshold important to the survival of the vegetation. The size of the droplets hitting ground at this region can be found for each case: jettison height above ground of 15 m and jettison height above ground of 45 m (see Fig. 10). The yellow arrow of this figure shows the direction of the wind (120°, 2 m/s) [12:48]. The model predicts about 95% of the fuel in this case should have a diameter of D_0 > 270 µm and make ground contact within 120 m from the position of jettison. This seems to be in reasonable agreement with the distribution of the darkened areas identifiable on the satellite image.

From Fig. 1 and Fig. 2 one gets the percentage of the entire mass equal or below D_{HT} = 200 µm as $P_{HT} = P(D \leq 200$ µm) = 1% to 2% and the percentage equal or below D_{LT} = 82 µm as $P_{LT} = P(D \leq 82$ µm) less than 0.1% to 0.2%..

3.5. Estimated Amount of Released Fuel

According to [25] the amount of fuel in the left wing tank (tank 3 see Fig. 9) at the final flight is estimated to about 700 kg. Assuming most of this is dispersed and spread in zone 1 and zone 2 (see Fig. 4), it seems based on a comparison of the darkened area of zone 3 with those of zone 1 and 2 that the amount dispersed in zone 3 is at least 10 times more, or equal to the estimated amount of fuel present in the tanks 1 and 4 (see Fig. 9).

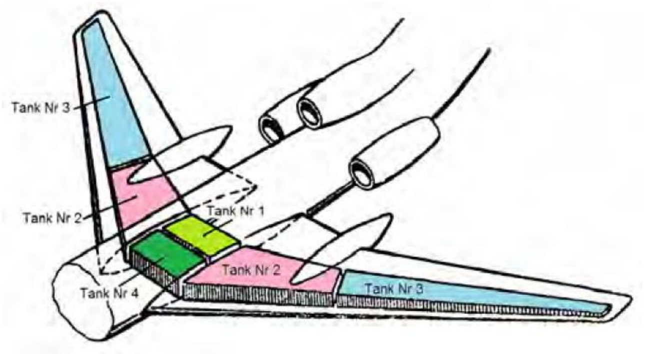

Fig. 9.. Tu-154M fuel tank configuration: No 1 -center wing tank (CWT), i.e., collector tank, No 2 - inner left and right wing tank, No 3 -outer left and right wing tank, No 4 - additional tank. [16].

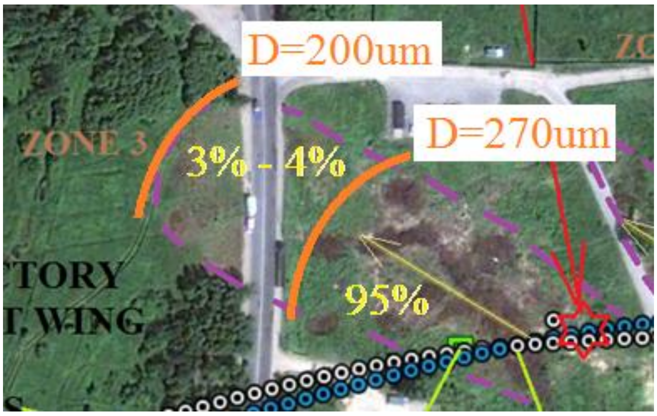

Fig. 10. The fuel distribution for the case of jettison height *H* = 45 m above the ground and an airplane speed of 75 m/s, *Tg* = 0°C and low volatile type jet fuel.

3.6. Estimated Ground Contamination Levels

Assuming a total mass of M =9900 kg during the jettison creating the damage of zone 3 rough estimates of the contamination can be found for the two areas of zone3: *near zone* closer than 120 m from the point of jettison and *far zone* more than 120 m away from this. On the satellite

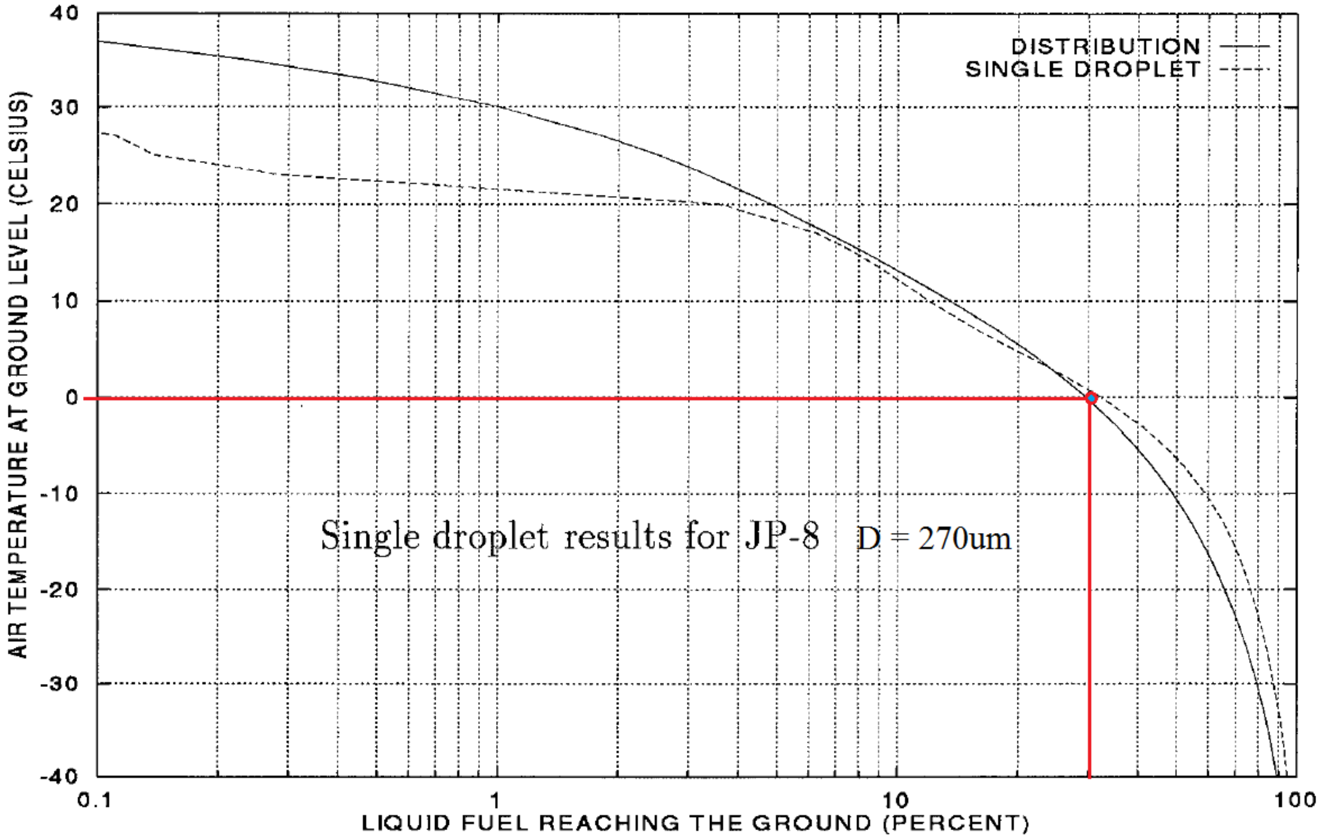

Fig. 11. From [1:56] . Single droplet plume released at Z = 1500 m for JP-8 fuel. The amount of liquid reaching the ground for air temperature at the ground of Tg = 0°C is η = 30%. Demanding the same result for D = 270 µm as found in this work predicts k = 0.022*10^{-6} m/s.

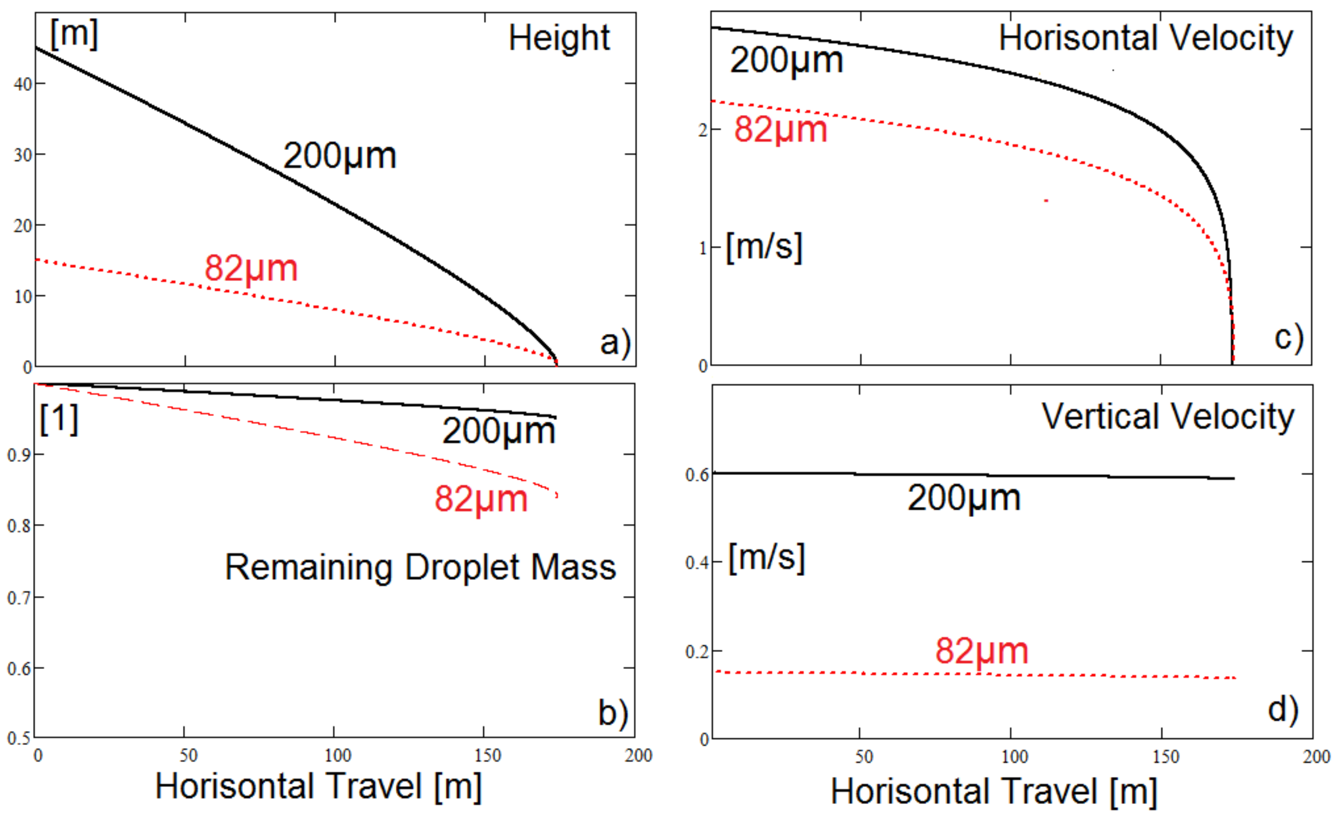

Fig. 12. Calculated Height (a), Remaining Droplet Mass (b), Horizontal Velocity (c) and Horizontal Travel (d) for two droplet sizes D = 82 µm starting at H_0 = 15 m (red curves), and a droplet of D = 200 µm starting at H_0 = 45 m (black curves).). In all figures the ground temperature, Tg = 0°C and low volatile JP-8 type fuel with k = 0.022*10^{-6} m/s.

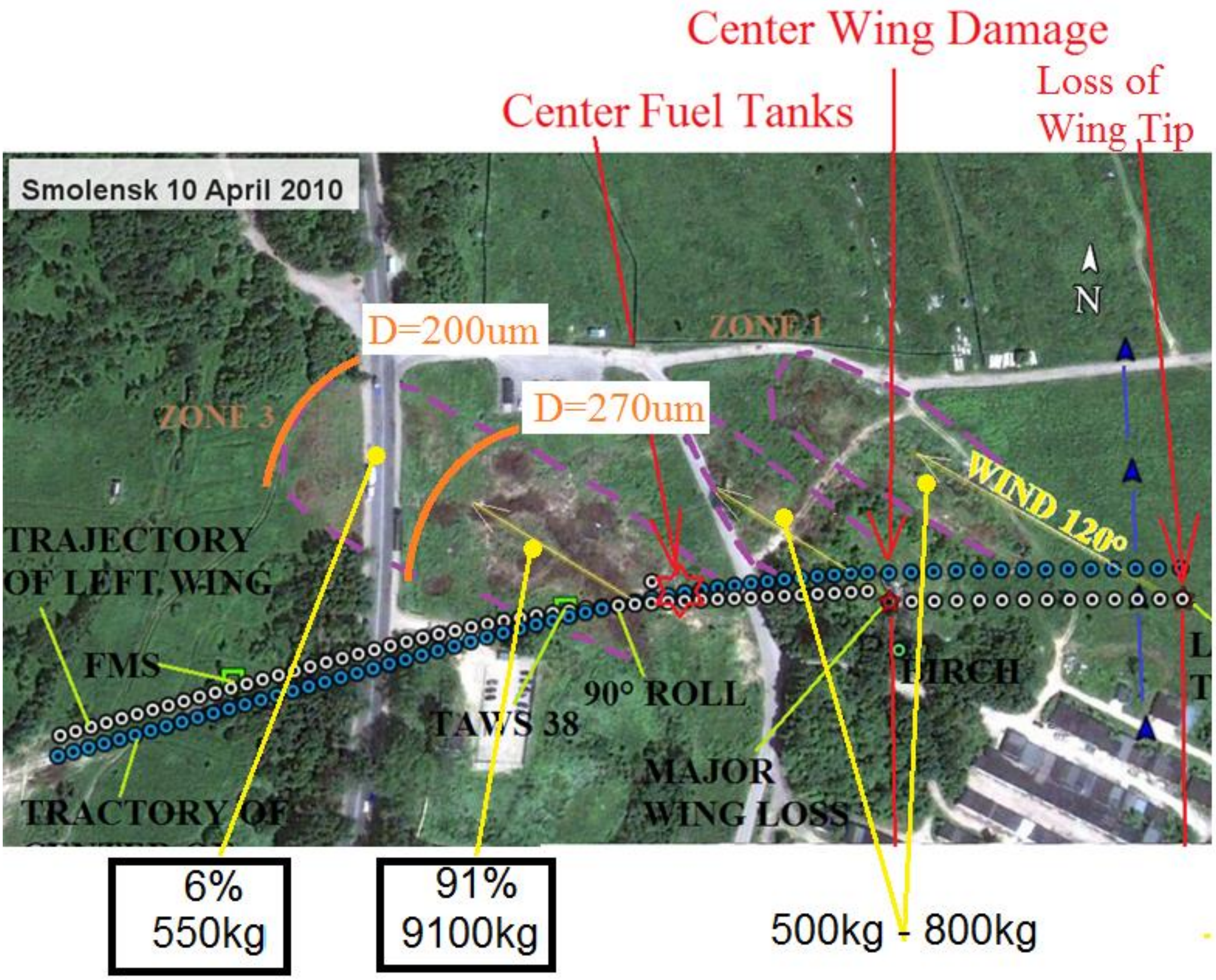

Fig. 13. The fuel distribution for the case of jettison height *H* = 45 m above the ground and an airplane speed of 75 m/s, *Tg* = 0°C and low volatile type jet fuel.

image the contamination seems to cover roughly half the area of the far zone (i.e. a distribution factor of $\chi = 0.5$), and assuming a width and length of this about $L = 50$ m and $W = 50$ m, one gets a contaminated area of $A_c = \chi LW = 1250$ m^2. Assuming the top 1-2 cm layer of vital importance to the grass vegetation one gets an approximate contamination of fuel of about $C_{\text{far}} = 9$ mg/g to 37 mg/g. In a similar manner the contaminated area in the near zone can be estimated as $A_c = \chi{*}L{*}W = 0.75{*}120\text{m}{*}45\text{m} = 4050$ m^2 and the average contamination of about $C_{\text{near}} = 77$ mg/g to 156 mg/g; of course with great local variations as can be seen in Fig. 8 (probably due to the incomplete jettison process at this low height and low air speed). Nearly 93% of all JP-4 spilled in soil biodegrades slowly, with the rate of degradation dependent on the soil type. The remainder of a soil spill evaporates rapidly. JP-4 can remain in some soils for 20 years or more [26]. As JP-4 is more volatile than A-1 type jet fuel, this goes for the A-1 jet fuel used by the TU-154M as well. On the other hand depending on the microbial biodegradation present in the soil, the contamination levels can be reduced within months after a spillage [27]. In [28] baseline toxicity tests were performed using Sorgum (*Sorghum bicolor* L.) and pinto bean (*Phaseolus vulgaris* L.) plants as baseline plants in a whole plant bioassay. JP-4 aviation fuel was mixed with the soil in individual test containers at different concentrations. The soils were flushed with water and the plants were watered on a regular basis. They concluded that the JP-4 fuel significantly affected the growth at all the investigated concentrations (6.5 mg/g to 50 mg/g). Sorghum plants decreased in height as the JP-4 concentration increased in the soil. From 1980 to 1989 the United States Air force Occupational and Environmental Health Laboratory (USAFOEHL) performed over 40 bioassays in response to field incidents. Of these roughly half were fuel related. Results from these 40 bioassays have shown that aviation fuel affects plants at concentrations as low as 1 mg/g. [28]. Based on these data it seems reasonable to assume that while even just 1 mg/g can affect the plants, it might be expected that concentrations above 5 mg/g may cause a distinct mortal effect on the vegetation.

The estimated contaminations therefore seem likely to cause the observed vegetation damage. The severely darkened area of zone 3 lies within a distance of 120 m from the trajectory. (See Fig. 10 and Fig. 13). The length of zone 3 is approximately 170 m and the width approximately 40 m at the beginning. Taking the plane velocity of $V_{\text{airplane}} = 75$ m/s into account, this indicates the fuel of zone 3 was released in less than 0.4 s. The yellow arrow in Fig. 13 marked "Wind" shows the direction of the wind (120°, 2 m/s) [12:48]. The model predicts about 91% of the fuel in this case should have a diameter of D_0 > 270 μm and make ground contact within 120 m from the position of jettison (red star). This seems to be in reasonable agreement with the distribution of the darkened areas as seen on the satellite image. Assuming the central fuel tanks both containing in total about 9900 kg is dumped in the zone 3 area results in about 550 kg reaches the far area resulting in contaminations of the top 1 cm to 2 cm soil of about 15 mg/g to 30 mg/g. (See Fig. 14) . The amount of fuel within this region of area A = 1000 m^2 is less than 1.6 kg for an airplane height of 15 m during the jettison. An airplane height of 45 m would send between 90 kg to 240 kg into this same region. An amount of M = 1.6 kg jet fuel type A1 spread over an area of 1000 m^2 does not seem likely to produce any significant damage to the vegetation. The resulting concentrations of the top soil layer are shown in Fig. 15 for four different distribution factors χ. Assuming the vegetation damage requires jet fuel concentrations of more than $C_{Threshold}$ = 5 mg/g, the minimum airplane height during the jettison can by this be found to be within 23 m to 52 m. The higher the threshold concentration the higher the airplane needs to be during the jettison to obtain the required concentrations. For a threshold concentration of, say, $C_{Threshold}$ = 30 mg/g in the top ΔT = 1 cm soil, and a distribution factor of χ = 0.25 to χ = 0.75, the airplane height during the jettison is found to be within H = 36 m to H = 72 m.

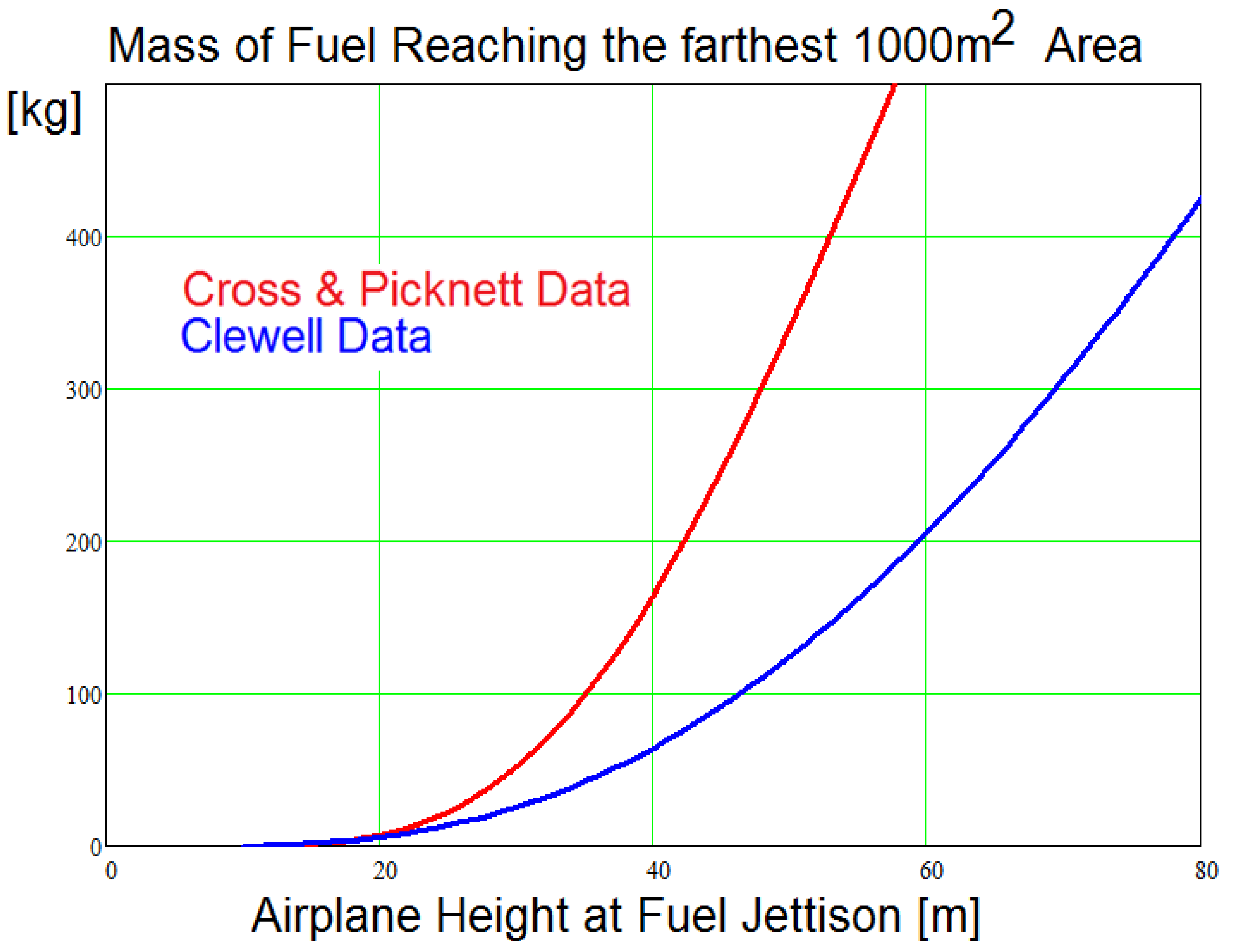

Fig. 14. The mass of jet fuel hitting the farthest 25 m long and 40 m wide region located at a distance of 148 m to 173 m from the jettison as a function of the initial jettison height for an airplane velocity of $V_{airplane}$ = 75 m/s.

The rest about 9100 kg fuel reaching the nearest 120 m from the point of jettison and resulting in contaminations of about 100 mg/g to 200 mg/g. From reporting's in literature of the effect of such contaminations it seems likely they were produced by the amount of fuel.

The model predicts the majority of the fuel droplets have a size of D = 270 μm or larger. This correlates well with Fig. 1 and Fig. 2 where it can be seen that about 95% of the droplets are expected to have a diameter larger than D = 270 μm.

The above results suggest that the damaged zone of vegetation cannot be produced by a jettison of the fuel occurring at a low trajectory height $H \approx 15$ m above the ground. The jettison necessary to produce the observed vegetation damage at this trajectory would require airplane speeds 2 times the speed of the Tu-154M at Smolensk.

The results suggest that the damaged zone of vegetation could be produced by a jettison of the fuel occurring at the high trajectory with height $H \approx 45$m above the ground from the airplane flying at the speed of 75m/s.

3.7. Missing Parts of the Skin of the Central Fuel Tanks

Fig. 16 is taken from [12:95] and shows the parts of the wreckage gathered after the crash by the Russian authorities. The skin (the bottom of the fuselage) at the region of the central fuel tanks seems to be missing. This could be the result of the fuel dump resulting in the zone 3 shown in Fig. 8 and Fig. 10. The Polish archeologists found parts from the TU-154M in the ground in a 120 m belt just passing the Kutuzov street about 100 m earlier than the crash site. The positions of these parts seem to be the likely ending position of parts torn from the plane at the third jettison event. Neither the missing parts of the plane nor the positions of the located parts on the ground before the crashsite, have been adequately documented by the Russian or Polish authorities. The Polish investigation team under the direction of Dr. Lasek explained the presence of airplane parts before the crash site as "*a result of alumina passing through the engines, and fired backwards from the crash site into the ground*". It is unclear how this could have happened and there is no detail documentation or evidence for such ability documented by Dr. Lasek. The authors have no knowledge of such phenomena been ever reported before. The positions of these parts correlate well with the estimated position of the jettison creating zone 3. Assuming the plane was about 45 m above ground the height differential between this point and the point where the parts were located allows for about 3 s of free fall. With an initial speed of 75 m/s this would result in about 200 m of horizontal travel of parts launched horizontally. Due to the position of the plane the parts would tend to be launched in a downwards direction, and the distance travelled would then be respectively shorter. The distance from the estimated position of jettison (and fuselage damage) to the center of the red circle shown in Fig. 17 is about 170 m.

The size of the zones of damaged vegetation as can be observed about two months after the crash correlate with the expected droplet size distribution based on experience gathered within the various studies of jettison of jet fuel done the past decades and the reported weather conditions at the time of crash. The work presented here strongly supports the hypothesis that the plane was 45 m or higher above the ground when the jettisons occurred in the three individual events. Large jettison rates tend to produce larger droplet diameters as the air resistance might not possess sufficient energy to thoroughly atomize all of the fuel. The fluid tends to slow down while breaking up, so the efficient airspeed for further breaking droplets from medium size to smaller size rapidly decreases over time from the initial release to the

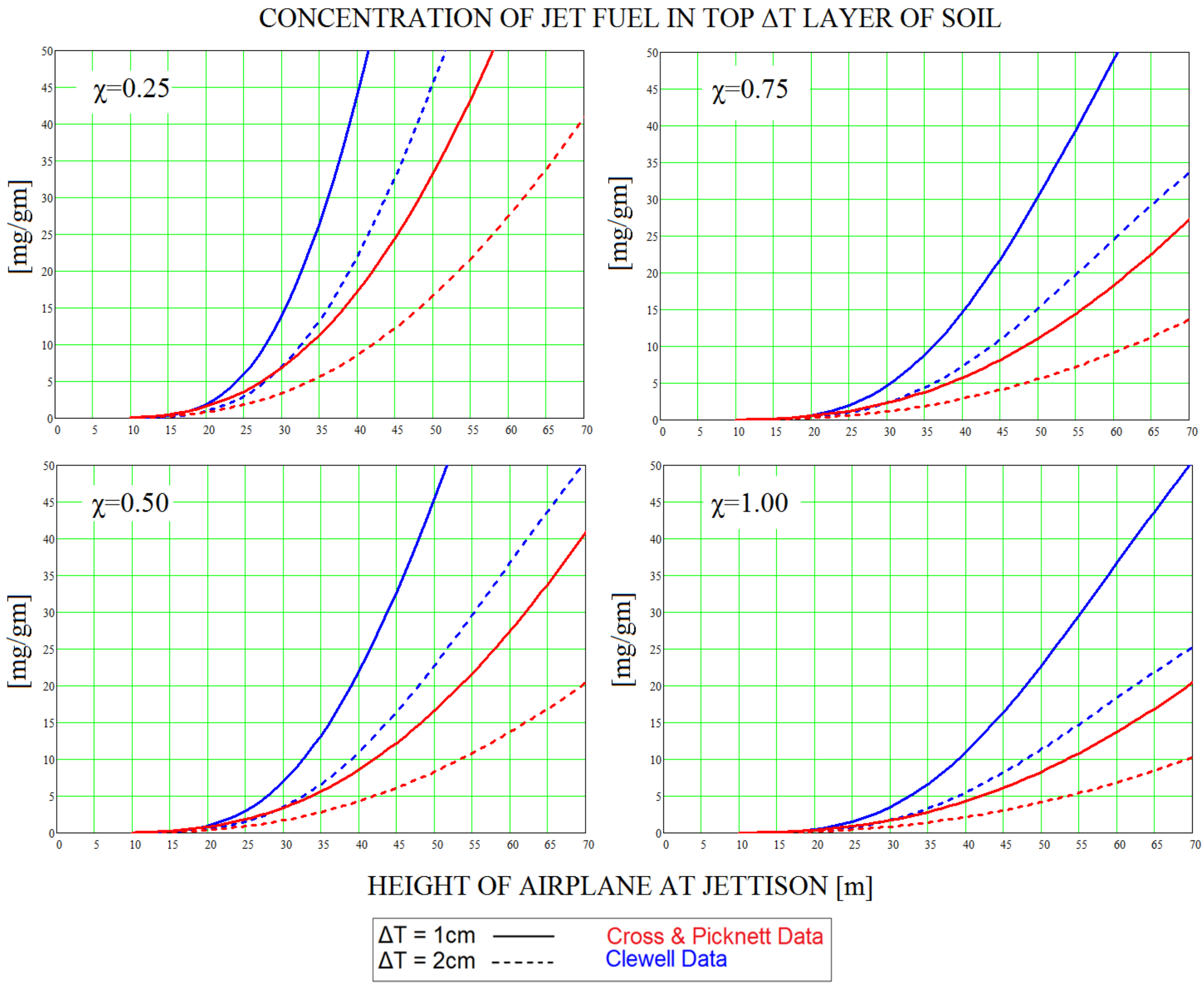

Fig. 15. The concentration of jet fuel for the farthest 25 m long and 40 m wide region in the top ΔT = 1 cm and ΔT = 2 cm layer of soil as a function of the initial jettison height performed with a velocity of $V_{airplane}$ = 75 m/s for four different distribution factors χ = 0.25, χ = 0.5, χ = 0.75 and χ = 1.00.

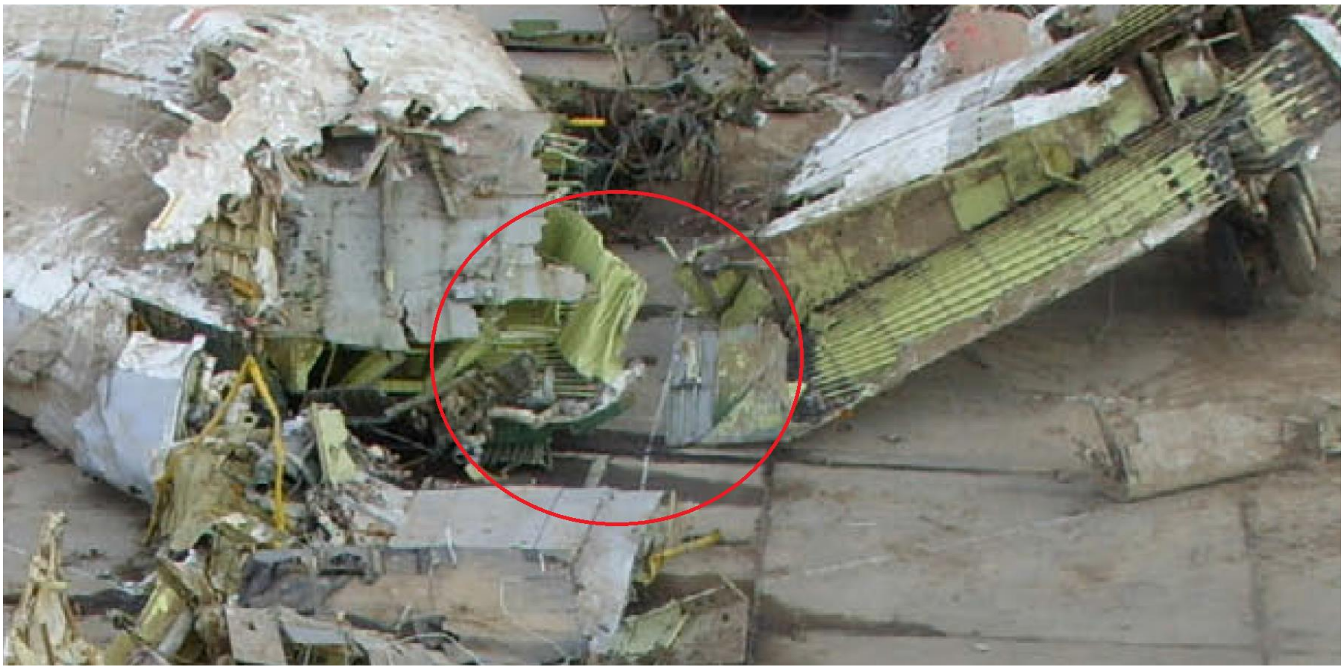

Fig. 16. The plane wreckage shows missing parts in the area of the central fuel tanks.

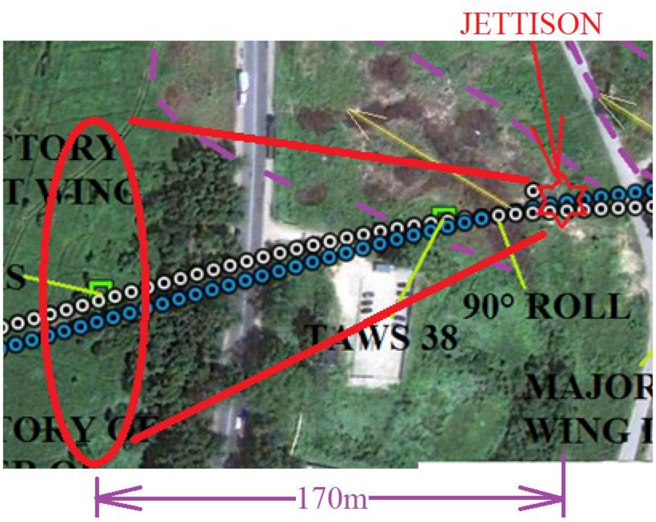

Fig. 17. The time of free fall of parts released from the plane during the dump of fuel from the central fuel tanks from H=45m at the position of the star shown above is about ΔT = 3 s. Conclusion

fluid velocity equals that of the ambient air. Judged upon the width of the damaged vegetation zones, in the case examined here the release of fuel is done in a rate that far exceeds the rates normally studied in the referenced work; and therefore, the droplet distribution found in this work is most likely underestimating the size of the actual droplets in this case. Including this effect will tend to further enhance the conclusions given here. The severe darkened area of third zone closest to the crash site lies within a distance of 120 m from the trajectory and position of the jettison. This implies that the majority of the fuel droplets have a size of D =270 μm or larger. This correlates well with the expected droplet size distribution, where it can be seen that about 91% of the droplets have a diameter larger than D = 270 μm. It seems very unlikely that the damaged zone of vegetation can be produced by a jettison of the fuel occurring at a low trajectory height say $H \approx 15$ m above the ground, as this would require a droplet distribution as seen with jettison air speeds of V = 150 m/s to V = 175 m/s with other words more than 200% to 230% higher than the case was in Smolensk (75 m/s) and jettison rates several magnitudes lower.

The estimated contaminations based on jettison of the remaining fuel in the central fuel tanks seem likely to produce the zone 3 of damaged vegetation as can be seen a couple of months after the crash in Smolensk. The fuselage skin covering the central fuel tanks seems to be missing, and airplane parts are found in the ground near Kutuzov street about 100 m earlier than the crash site. The positions of these parts seem to correlate with the predicted ground hit of parts originating from the estimated position of the last jettison creating the largest zone of damaged vegetation (zone 3).

4. Conclusion Summary

- The zones of damaged vegetation east of Runway 26 in Smolensk 2 months after the crash can be produced by a fuel release to the air occurring in 45 m height above the ground by an airplane flying 75 m/s.
- The damaged vegetation zones correlate extremely well with the earlier calculated positions of wing damage based on the aero dynamic work as well as the trajectory based on the recorded GPS data and recorded vertical acceleration data.
- Less than 1.6 kg fuel will reach an area of 1000 m^2 located 148 m to 173 m from the jettison performed by an airplane flying at 15 m height with 75 m/s given the reported wind speeds and temperatures.
- About 100 kg – 240 kg fuel will reach an area of 1000 m^2 located 148 m to 173 m from the jettison performed by an airplane flying at 45 m height with 75 m/s given the reported wind speeds and temperatures.
- If the zones of damaged vegetation were to be produced in 15 m height above the ground the required airplane speed would need to be 150 m/s to 175 m/s or at least 2 times the speed of the TU-154M on the 10th of April 2010.

- The three damaged zones can not be explained within the official crash hypothesis as both the position of the zones as well as the number of zones (3) does not agree with this hypothesis.
- Based on this work it is very unlikely that the TU-154M was flying below 30 m when the fuel release occurred.
- The resulting ground contamination levels based on the droplet size distribution profile points towards the third zone of damaged vegetation (closest to the crash site) being produced by an amount of fuel equal to the central fuel tanks (about 9.9 ton).
- The bottom skin of the central fuel tanks as seen by the photo of the gathered wreckage after the crash is missing.
- Parts from the TU-154M are found in the ground west of the Kutuzov street 100m before the main crash site. The location of these parts correlate with the expected location of the ground hit of parts released from the TU-154M at the estimated position of the third jettison.

5. FURTHER WORK

Narrowing the critical threshold concentration, above which the vegetation cannot survive, will allow a narrowing of the airplane height during the jettison. This can require further experiments to be performed.

Note

A different version of this article has been submitted for publication in the MCFNS journal.

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