ANTI-ICING NOZZLE PARTICLE REJECTION

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1. Abstract

The introduction of fixed anti-icing systems has raised issues regarding these systems relationship to other winter maintenance activities. These systems automatically dispense a deicing agent on a targeted surface by means of specially designed anti-icing spray nozzles. These systems permit the immediate treatment of a targeted surface in either an anti-icing or deicing mode. These systems have proven to be advantageous in addressing microclimates where black ice and frost are common or at remote or congested sites were logistical problems with trucks are encountered. These anti-icing systems find further application in areas with high winter accident rates and on structures where non-corrosive deicing agents are desired.

A variety of anti-icing nozzles are available to accommodate specific structures. One of the popular anti-icing nozzle designs is the flush deck nozzle. These nozzles are positioned in the roadway such that the top surface of the nozzle assembly lies flush with the wear course. This placement is required so the nozzles may be placed anywhere on the road without becoming damaged by snow plowing operations, tires or other surface hazards. However, because of the nozzle’s positioning, particles that are encountered on a roadway, such as abrasives, can settle into the nozzle openings. This paper reports on the effectiveness of the nozzle’s particle rejection of common abrasives.

2. Introduction

Fixed anti-icing systems have recently been introduced to the roadway infrastructure and present us with new considerations. Fixed anti-icing spray technology (FAST) was introduced to provide immediate chemical protection to areas highly prone to ice and frost. They work particularly well in addressing microclimates that frequently produce ice and frost conditions. They find further application on surfaces which produce exceptionally dangerous conditions when covered by ice, such as intersections, sharp curves and remote locations where logistical complications prevent treating troublesome areas. The most important issues raised by these systems are 1) effectiveness, 2) driver perception and 3) durability. To provide an initial insight into the durability question, we present an investigation on flush anti-icing nozzles and their ability to reject common abrasives. One of the most popular anti-icing nozzles is one referred to as the flush nozzle. These nozzles are positioned in the roadway so that the top of the nozzle is flush with the wear course. This mounting scheme is employed to prevent damage to the nozzle by snow plowing operations, tires or other surface hazards. However, because of this positioning, abrasives and other foreign materials can potentially block the discharge area of the nozzle.

3. Background

FAST systems are attractive because they permit the immediate chemical treatment of a targeted surface in either an anti-icing or deicing mode. The systems are activated by various user interfaces such as telephones, pagers or radio. Additionally, fully autonomous systems employ RWIS data to directly activate the FAST. Typically these systems use a remote pumping station to pump a deicing chemical through a series of nozzles located at strategic points in or along the roadway. Typically, the nozzles are sprayed one at a time and dispense a film of chemical that is tracked fully along the targeted surface by vehicular traffic. The tracking characteristic varies by chemical but has been found to carry over 150 M [1].

Various chemicals such as calcium chloride, magnesium chloride, sodium chloride, calcium magnesium acetate, potassium acetate and potassium formate are commonly employed as deicing agents. However, the materials that are encountered on a road surface are very broad. Abrasives are often added to the road to enhance tire traction and these particles can present a source of potential nozzle pluggage. These materials are typically naturally occurring materials such as sand and crushed rock, or the products of combustion such as bottom ash, slag and cinders. Ore tailings are also used in many areas. They are usually specified to be "hard and durable" without clay or loam. Frequently, the particles are specified to be between #4 and #50 mesh (4.76 mm and 0.297 mm) [2].

The requirement for clearing obstructions from the nozzle slots is driven by the fact that multiple nozzle discharges exist in all flush nozzle designs and that any obstructions must be cleared quickly to permit good spray coverage on a targeted surface. Moreover, the spray must not be disturbed in a fashion that permits it to spray high enough off the roadway to distract a motorist, such as by spraying a windshield. The ideal configuration for nozzle monitoring would consist of flow monitoring of each nozzle opening, this would be expensive, as a typical flush nozzle has at least four nozzles contained within it. However, RWIS data provides the most appropriate feedback on the spread of deicing chemicals in that it records the surface characteristics of the roadway itself and not just at the nozzle. Moreover, the observations of chemical tracking on these systems suggest that full coverage from each nozzle is unnecessary.

Obstructions in the nozzle slots could be freed by tire action, nozzle spraying action, snowplow shearing and similar shearing events. As a tire rolls over the road debris, the tire will drive the material into or out of the slots. The rolling surface of a tire provides forces in nearly all orientations. The downward vertical forces applied to nozzle slot debris is deleterious in that it drives the particles into the slots; however, the upward forces, although certainly not equal to the downward forces, are advantageous in liberating the particles from the slots. Sliding surfaces across the nozzle will either drive the material into or out of the slot depending on the orientation and geometry of the particles. When the nozzle sprays, high velocity liquid will impinge on any debris and through momentum transfer tend to force the particles out. However, the radial spreading of the jet flow results in a rapid diminishment of the momentum and kinetic energy of the fluid. As the jet travels, a field of droplets and induced air develops outside the fluid core in the center. Droplets form as a result of a combination of turbulence, aerodynamic interactions and surface tension. The droplet size and the time required for them to form is characterized by the Weber number:

$$We = \frac{\rho^2 V^2 d}{\gamma} \tag{1}$$

Where,

ρ = gas phase density
V = relative velocity of the droplet to the gas velocity
d = droplet diameter
γ = surface tension

In the case of water in air, the minimum critical Weber number for developing droplets range from 10 to 20 [3].

The nozzle discharge area is essentially a protective portion for the nozzles. This area is designed to maintain roadway ride quality, protect the nozzles from damage and, to the extent possible, prevent obstructions to the nozzle. These design options are limited, when not considering mechanical nozzle covers and similar appurtenances. The design of the nozzle discharge area may either be slots of different geometry, a completely open nozzle discharge area or tunnels that connect the nozzle egress to the roadway surface. The problem with a completely open nozzle discharge area is that a large piece of debris could settle in the nozzle discharge area and would never be dislodged by either the spray or tire action. The geometry of this type of debris would be wide and flat, such as a piece of sheet metal, glass plate, or shale. As the slots are made narrower, the particles that can become engaged in the slots becomes smaller and, because of their lower mass, presumably easier to dislodge by the momentum transfer of the chemical spray. Tubular discharge areas require a larger nozzle assembly diameter in order to maintain a sufficient wall thickness above the tubes.

There are three conditions to consider when investigating the obstruction of anti-icing nozzles. The first obstructing condition is when a large particle is forced into the nozzle discharge area and wedged into a fixed position. The second obstructing condition is when particles of road debris are mixed with a fluid to produce a slurry and third, which is really a continuum from the second condition, in which completely dry particles are compacted into the nozzle slots.

4. Characteristics of Obstructions

Slurry

One form of obstructing debris in the nozzle discharge area will be a slurry of particles and fluids. The composition of this slurry is polymodal with small particles filling the interstices of larger particles. The supernatant liquid will be any of the fluids present in a roadway environment such as water, deicing chemical, gasoline, oil, and hydraulic fluids. Slurries are not Newtonian fluids; as the solids loading of slurries increase, the supernatant liquid is insufficient to fill the interstices between the particles. Consequently, the particles actually touch each other and the slurry becomes very dilatant, at high shear rates, owing to the frictional forces between the particles. Conversely, slurries are typically psuedo-plastic at low shear rates.

Slurry particles are subjected to colloidal forces as well as hydrodynamic, gravitational, inertial, viscous, and thermal forces. The colloidal forces can be electrostatic, steric, and London van der Waals forces. Hydrodynamic forces consist of the viscous drag of the supernatant liquid and the flow field disturbance created by a neighboring particle. The thermal forces are caused by molecular collisions. Inertial and viscous forces become increasingly important with increasing particle size while colloidal forces become more important with decreasing particle size. The rheology of this obstructing slurry is controlled by the balance of these forces.

Insights into the effect of particle size on rheology can be obtained by looking at non-interacting spheres [4]. Experiments in which glass spheres were suspending in an aqueous and non-aqueous medium of equal density to avoid sedimentation found that viscosity increased greatly with decreasing particle size in the aqueous medium but was independent of particle size in the non-aqueous medium.

This evidence suggested that this relationship was due to the fact that in the aqueous medium, each glass sphere was surrounded by a layer of fluid which greatly increased its effective size. The resulting increase in volumetric concentration is the largest for the smallest particle size.

Sweeny and Geckler [4] conducted experiments with a structure of glass spheres in order to test the affect of particle size distribution on viscosity. They found that two types of interstices were formed in a close packed monomodal system. The first is a reversed spherical cube that can fit a sphere with a diameter up to 0.414 times the size of the spheres constituting the system. The second is a reversed spherical tetrahedron that can accommodate a sphere with a diameter up to 0.225 times the size of the bigger spheres. To study the effect of adding different sizes of spheres, they used spheres that were too large to fill the cubic interstices, then spheres that were small enough to fill the cubes, followed by spheres small enough to fill the tetrahedron and finally spheres that could move freely through the system. This experiment indicated that the viscosity at rest increased a little initially when proceeding to smaller particles, or a larger diameter difference, and then decreased at higher shear rates.

This experiment also indicated that a wide particle size distribution would reduce the viscosity of a system by increasing the modality of the slurry. Particles with smaller diameters will fill the interstices of the larger particles throughout the range of particle sizes. However, if there is a preponderance of a particular size, there may not be enough small particles to fill the interstices of the dominant particle size. In this case, a mixed composition results, with localized bimodal and monomodal groupings.

For the subject slurries, sedimentation and subsidence should be expected because no surfactants are integrated in the slurry. Sedimentation is the settling motion of large particles relative to small ones that can appear in well-dispersed slurries. Subsidence is the settling motion of all particles relative to the supernatant liquid and occurs in slurries with some flocculation.

Large Particle Obstructions

The other phenomenon that can produce nozzle obstruction is that of large particles lodging in a nozzle discharge area. These particles can be forced into an open area and are principally bonded by material yielding at asperity contacts. When considering this phenomenon, the delivery mechanism of the particle must be considered. Wind blown particles that can engage the nozzle discharge area by the force of gravity alone are contributors to the slurry obstruction described previously. Due to the high modulus of elasticity of the engaging surfaces, gravitationally loaded particles will not cause significant obstructions on their own. However, when a particle is forced into the nozzle discharge area by tire pressure or other powerful application means, the particle can indeed become entrapped in the nozzle discharge area. The particle size that can engage the nozzle discharge area is a function of the size of the nozzle discharge area as well as the geometry of both the particle and nozzle discharge area.

We are not considering nozzle discharge area wear in this work; however, the adhesive wear caused by large particle obstruction is one of several wear mechanisms acting upon the nozzle discharge area. These mechanisms also include abrasive, surface fatigue and tribochemical wear. Abrasive wear is caused by plowing of two materials in which a material is then plastically deformed and fails. In surface fatigue wear, fatigue caused by cyclic stresses initiate and propagates cracks. These cracks grow large enough to cause flaking of surface material. The tribochemical wear mechanism is a combination of mechanical and thermal processes at the contact interface which increases the corrosiveness of the surface.

Where no fluid is present, friction is produced between particles where the peaks (asperities) and valleys of the particle surfaces interface. This contact area is much smaller than would be provided by an apparent contact area of a perfectly smooth surface. Generally, the smallest of these asperity junctions contact one another under highly localized pressure and therefore deform plastically [5]. With further load however, the larger asperities engage each other and the contact area increases. These asperities deform elastically because of the large contact area. With many metals and brittle materials the mechanism of plastic deformation is an anisotropic "slip" in which planes of atoms slip over each other. As the load increases, a critical shear stress is achieved causing plastic deformation within the zone of elastic deformation. Clearly the task of quantifying asperities is difficult because of the small contact asperity junctions and the subsequent alacrity in which they deform. Moreover, the contact of two curves surfaces present the interesting condition of triaxial stress which were first studied by Hertz.

One of the material yield criteria that can be applied to the asperity contact, based on Tresca's maximum shear stress, is [6]:

$$\frac{Y}{2} = k = \text{Max}\{\frac{1}{2}\,|\sigma_1\text{-}\sigma_2|\,,\ \frac{1}{2}\,|\sigma_2\text{-}\sigma_3|\,,\ \frac{1}{2}\,|\sigma_3\text{-}\sigma_1|\,\} \qquad (2)$$

Where,

$\sigma_1, \sigma_2, \sigma_3$ are the principal stresses.
k = shear
Y = tension or compression

Therefore, the yield point is one half the yield stress in tension or compression.

Another criteria that can be applied here is the von Mises shear strain energy criterion. This criterion is based on yielding occurring when the distortion energy rises to equal the distortion energy at yield in pure shear or tension. This criterion gives:

$$\frac{Y^2}{3} = k^2 = \frac{1}{6}\,\{(\sigma_1\text{-}\sigma_2)^2 + (\sigma_2\text{-}\sigma_3)^2 + (\sigma_3\text{-}\sigma_1)^2\} \qquad (3)$$

Where,

$\sigma_1, \sigma_2, \sigma_3$ are the principal stresses.
k = shear
Y = tension or compression

Therefore, the yield stress in pure shear is $\frac{1}{\sqrt{3}}$ times the yield stress in simple tension or fifteen percent higher than predicted by the Tresca criterion.

For axisymmetric contact of two spheres, the maximum shear stress occurs beneath the surface on the axis of symmetry. The derivation will not be shown here, however by Hertzian analysis:

For a Poisson ratio of 0.3,

$$\frac{1}{2}\,|\sigma_z\text{-}\sigma_r| = 0.31\ p_o \text{ at a depth of } 0.48\ a$$

Where,

p_o = maximum contact pressure
a = contact radius

Therefore by the Tresca criterion, the yield value is given by,

$$(p_o)_y = \frac{3}{2}\,(p_m)_y = 3.2\ k = 1.60\ Y \qquad (4)$$

Where,

$p_m =$ mean contact pressure

While von Mises gives:

$$(p_o)_y = 2.8\ k = 1.60\ Y \tag{5}$$

Therefore, the load, W, to initiate yield is given by Hertzian analysis:

For a composite modulus of elasticity equal to:

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{6}$$

Where,

E^*= composite modulus
E_1 = modulus of elasticity of nozzle
E_2 = modulus of elasticity of obstruction

Therefore,

$$P_o = \frac{3}{2} P_m = \frac{3W}{2\pi a^2} = \left[\frac{6WE^{*2}}{\pi^3 R^2}\right]^{1/3} \tag{7}$$

And,

$$W_y = 21.17\ R^2 Y \left(\frac{Y}{E^*}\right)^2 \tag{8}$$

In order to carry a high load without yielding the nozzle material should have a high yield strength and a low modulus of elasticity.

The distribution of these stresses is interesting to note. A spherical band of tensile hoop stress develops around the point of contact and prevents the expansion of the plastically deformed material. This band produces a peak hoop stress at the surface, which delineates the tensile radial forces outside the band and the compressive stresses within it. This stress distribution is the cause of surface cracking in non-hardening materials. For hardening materials the peak stress does not reach the surface.

5. Experiments

The test equipment employed in this evaluation was a standard nylon Odin Systems Flush Nozzle with standard and modified nozzle discharge area slots. The test assembly consisted of a centrifugal pump, pressure regulating valve and gate valve. The test nozzles were attached to the assembly and were subject to various obstructions. Under full flow conditions the maximum pressure at the nozzle manifold feed was 550 kPa. The criterion for determining that obstructions had completely cleared the nozzle discharge area was that it must do so in less than one second after commencement of spraying.

Two types of nozzle discharge were used. The first nozzle slot design had straight edges and the second employed chamfered edges. Both of these designs used four nozzles fed by a common manifold and discharging through slots with a width of 4mm. The chamfer design was a simple radius of 1.1 mm. Based on visual observation, the fluid core was intact during the 80 mm of nozzle slot travel.

Representative samples of anti-skid materials were collected from Maryland, Pennsylvania and New York, USA facilities. All the materials except sand were mechanically crushed and had sharp edges as in the regions tested spheroidal anti-skid materials are unpopular with many transportation personnel because they claim that they tend to bounce off the roadway when applied.

Slurry Testing

Polymodal slurries and dry particles were packed into the nozzle slots and loaded with 90 kg of vertical force. Slurries were made using particles under 2 mm with the following supernatant liquids. Water, brake fluid, light oil and gasoline. A dried composite and a water-based slurry that was allowed to dry for 24 hours were all tested. All slurries and dried particles were discharged from the nozzle slots at or under 128 kPa and 0.16 l/s flow rate.

Large Particle Testing

For this test various anti-skid materials were laid on top of the test nozzle. The nozzle and anti-skid material were rolled over at a slow speed with a tire loaded at 420 kg. The low speed of tire advance does not duplicate the dynamics of normal highways but it offered a consistent means of loading the debris and simulating the orientation of tire loading upon the debris. Moreover, it is important to note that the percentage of cleared particles at minimum pressure and flow cannot be inferred from the data presented. This is because multiple particles can align themselves side by side in the nozzle slots. The measurement of cleared particles is for reference only and is based on 360 nozzle slot tests.

Results

All sands with a particle size under 2 mm discharged at or under 138 kPa pressure and 0.16 l/s flow rate.

Table 1 illustrates the fluid pressure required for particles that required more than 138 kPa to dislodge. The particles that did not dislodge at 550 kPa were collected and tested further. No surface cracking or plastic yielding was observed on the nozzle surfaces.

Table 1

Pressure (kPa)	Quantity
172	1
207	1
241	2
276	1
345	4
414	3
483	2
517	2
550	3
> 550	8

Characterization of Obstructing Particles

The following are the dimensions for all the rocks that lodged in nozzle slots when exposed to the maximum test system spray pressure of 550 kPa and a flow rate of 0.39 l/s. All particles had sharp, linear edges.

Table 2
Dimensions of Obstructing Rocks (mm)

Axis	Major	Minor
	5.4	3.0
	7.6	3.2
	4.9	2.3
	3.9	2.9
	6.2	3.0
	9.0	3.7
	6.8	3.5
	7.8	3.4
	14.1	3.4
	5.3	1.2
Average	7.1	3.0
Mean	6.5	3.1
Standard Deviation	2.9	0.73

The two rock particles that fall outside of one standard deviation require some explanation. The 14.1 mm by 3.4 mm particle was triangular and had only a small portion of its triangular shape in the nozzle slot. The narrow, 3.4 mm portion of the particle is the most telling. The 5.3 mm by 1.2 mm rock was a plate-like piece of crushed limestone with very sharp lineal edges that was lodged in the middle of the flow stream and did not disturb the flow like the larger rocks. Omitting these particles gives:

Table 3
Dimensions of Obstructing Rocks (mm)

Axis	Major	Minor
Average	6.4	3.1
Mean	6.5	3.1
Standard Deviation	1.7	0.43

Particle Engagement of Slot during Drop Test

For this series of testing, two representative particles that were lodged in the nozzle slots from previous testing were dropped 60 times from a height of 25 mm above a nozzle slot. The number of times the particle landed in any manner that engaged the slot was recorded. This resting position would locate the particle so that it could be potentially forced into the nozzle slot. The dynamics of tire and other forces are not modeled in this study. Therefore, the numbers presented are for comparison only. Presumably, not all of the particles resting above a nozzle slot would be driven in. Their propensity to do so would be a function of factors ranging from the orientation of the nozzle slots with respect to the tire travel to the mass of the applied load.

1. Particle Tested: 5.4 mm x 3.0 mm

Nozzle Slot Description	Chamfered	Unchamfered
Particles Engaged	37%	18%

2. Particle Tested: 7.6 mm x 3.2 mm

Nozzle Slot Description	Chamfered	Unchamfered
Particles Engaged	50%	28%

6. Conclusions

This study evaluated potential obstructions to a FAST flush nozzle employing nozzle slots in the discharge area. The study findings indicate that slurries or particles smaller than the nozzle slot width do not represent a practical problem in obstructing spray discharge. Moreover, it suggests that particle obstructions with an average size of 6.4 mm by 3.1 mm will be the most problematic for a 4 mm wide slot, with the minor dimension being the culprit. It further suggests that chamfering of nozzle slots, which helps both the entrance and exit of two mating surfaces, increases the likelihood that particles will cause spray obstruction. This relationship between particle size and slot width provides nozzle design guidance for this type of nozzle discharge area. This study further suggests that the nozzle material should be of high yield strength and low modulus of elasticity.

Photograph Captions/Photographier des Sous-titres

Figure 1
Dried slurry testing.
Emulsion de particule sèche essai.

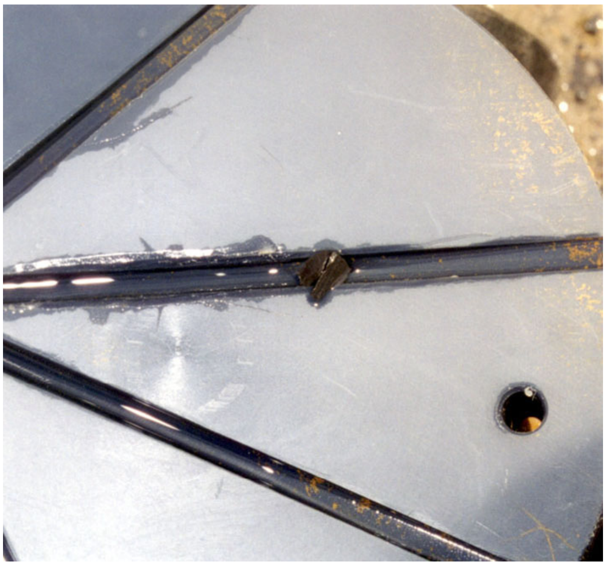


Figure 2
Typical obstructing particles
shown in nozzle slot.
Les particules typiques qui
encombrent montrées dans l’entaille de jet.

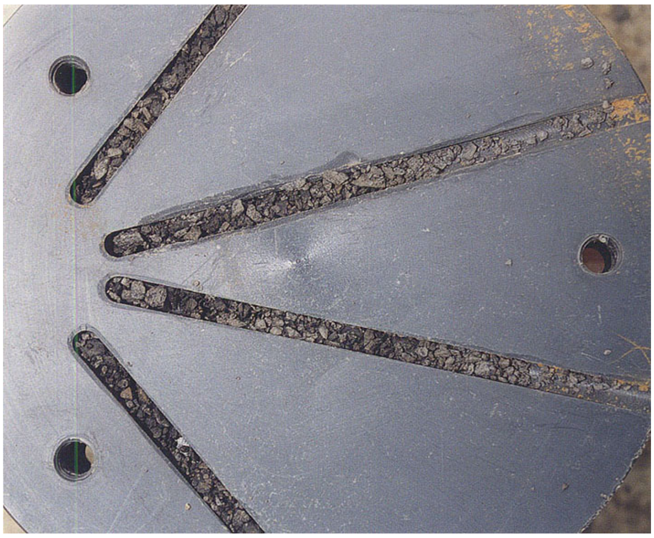
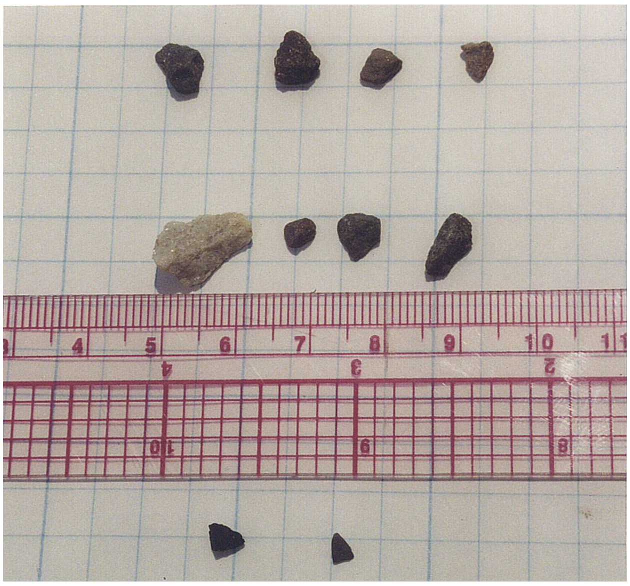


Figure 3
Obstructing particles.
Particles qui encombrent.



References

1. Based on a telephone interview with William Bebb, formally with Nebraska Department of Roads. Mr. Bebb has monitored a NDOR magnesium chloride-based FAST system on Interstate 80 near Kearny, Nebraska USA for two years. Mr. Bebb stated that chemical tracked, based on visual observations, up to 915 M. Normal truck-based anti-icing practice in Kearney is to treat an area 305 M in advance of a targeted surface. The vehicles track the chemical forward and this provided a time delay in treating the targeted surface.

Based on a personal interview with Mike Layman of the Maryland State Highway Administration. Mr. Layman has monitored a MSHA calcium magnesium acetate-based FAST system on Interstate 68 near Cumberland, Maryland USA. Mr. Layman states that he has visually observed tracking up to 91 M.

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Biography for Thomas Ask

Thomas Ask, P.E. is the Vice President for Engineering for Odin Systems International, Inc. Previously, Mr. Ask was President of Ask and Associates, a Senior Engineer at Ingersoll-Rand Company and a Research Engineer at the University of Illinois. Mr. Ask is the author of the Handbook of Marine Surveying as well as technical papers on slurry atomization, combustion and expert systems. Mr. Ask is a licensed Professional Engineer and a member of the Society of Automotive Engineers and their Airport Snow and Ice Control Equipment Subcommittee.

Biography for Bernie Ask

Bernie Ask is the CEO of Odin Systems International, Inc. Mr. Ask is the leading expert on fixed anti-icing systems based on his experience in developing Odin’s business. Mr. Ask has over 20 years of management experience and has authored numerous articles on fixed anti-icing systems as well as received several patents on anti-icing systems and components.