Inclement Weather
&
Aircraft Engine Icing

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GE Aviation

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Causes of Engine Icing

- Super-cooled droplets
- Mixed Phase atmospheres
- Ice Particles
  - Glaciated clouds (crystals)
  - Snow
  - Hail

Engine Manufacturers Certify to Several Inclement Atmospheres, all can contain an icing threat

- Icing
- Rain
- Hail

Engine Icing Effects

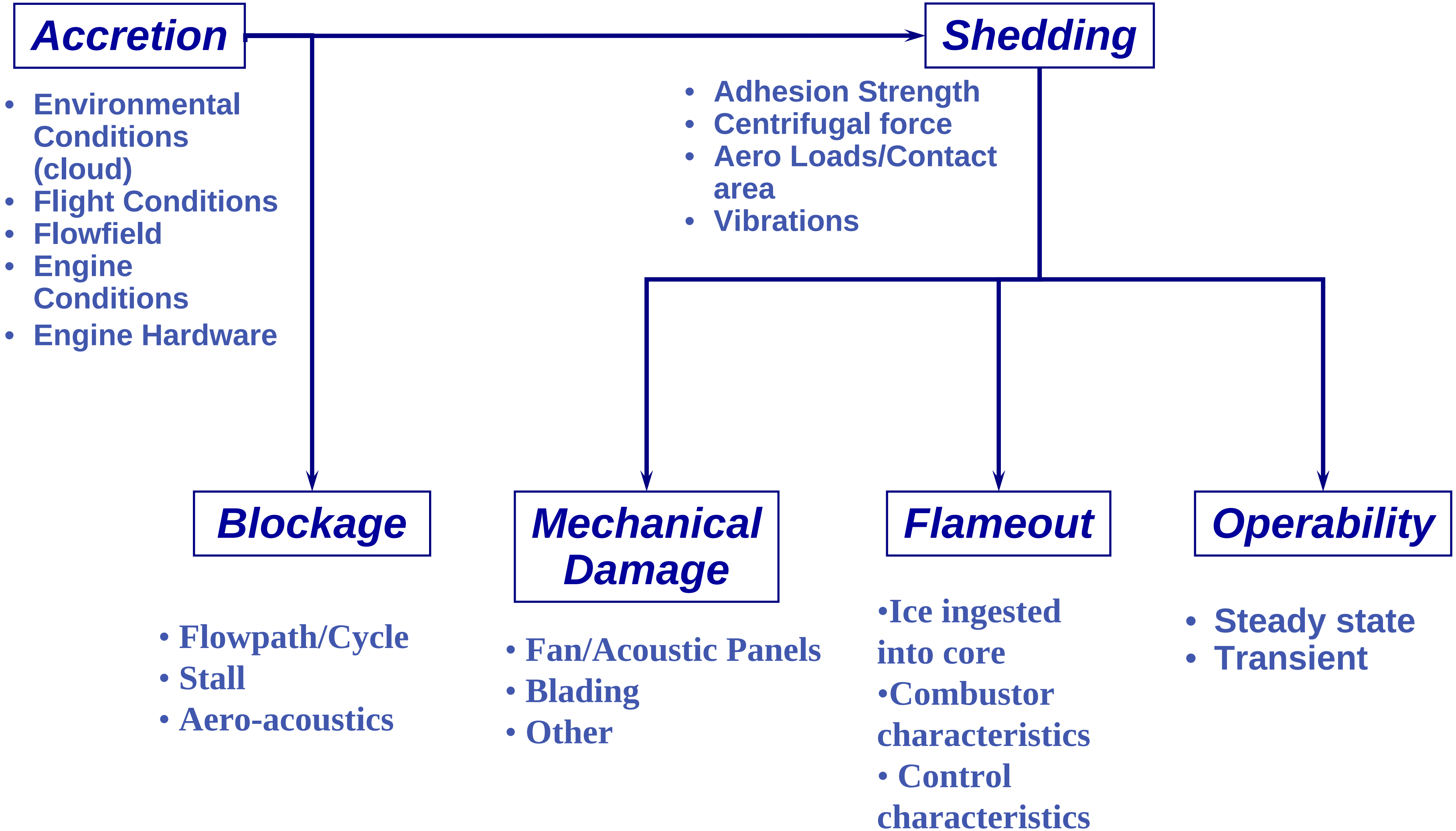
> Vibration

> Operability
  - Stalls / surges / resonances
  - Rollback
  - Flameout
  - Slow Acceleration

> Temporary thrust/power loss
  - Ice accretions cause aerodynamic losses, rotating stall etc.
  - Cycle changes

> Damage
  - Ice sheds can damage rotating blades, excite resonances

Engine Icing Design Considerations - Overview



Where does ice accrete ?

- Inlets
- Fan blades & spinners
- Cooler section static surfaces
- Forward booster/IP stages for "classical" icing
- Deeper into primary flowpath stages for "crystal" icing
- Sensors
- Bleed systems

Classical Icing Mechanisms

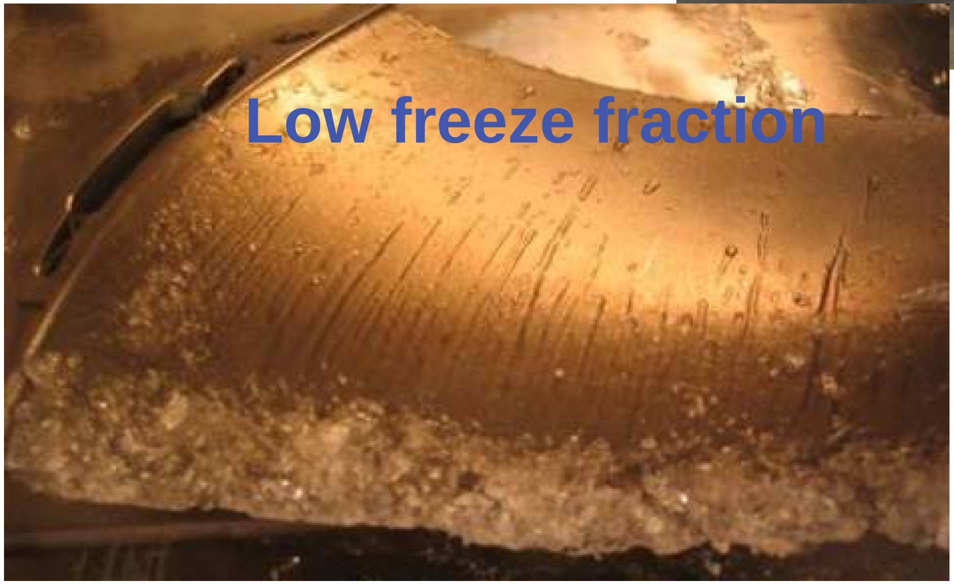
> Ice forms when super-cooled droplets impact & freeze on sub-freezing surfaces

> Ice forms due to runback from non-evaporative anti-icing systems – typically SLD (super-cooled Large Droplets – freezing rain or drizzle)

Super-cooled Droplet Accretion

Spinner ice

Runback Ice



Crystal and Mixed-Phase Icing

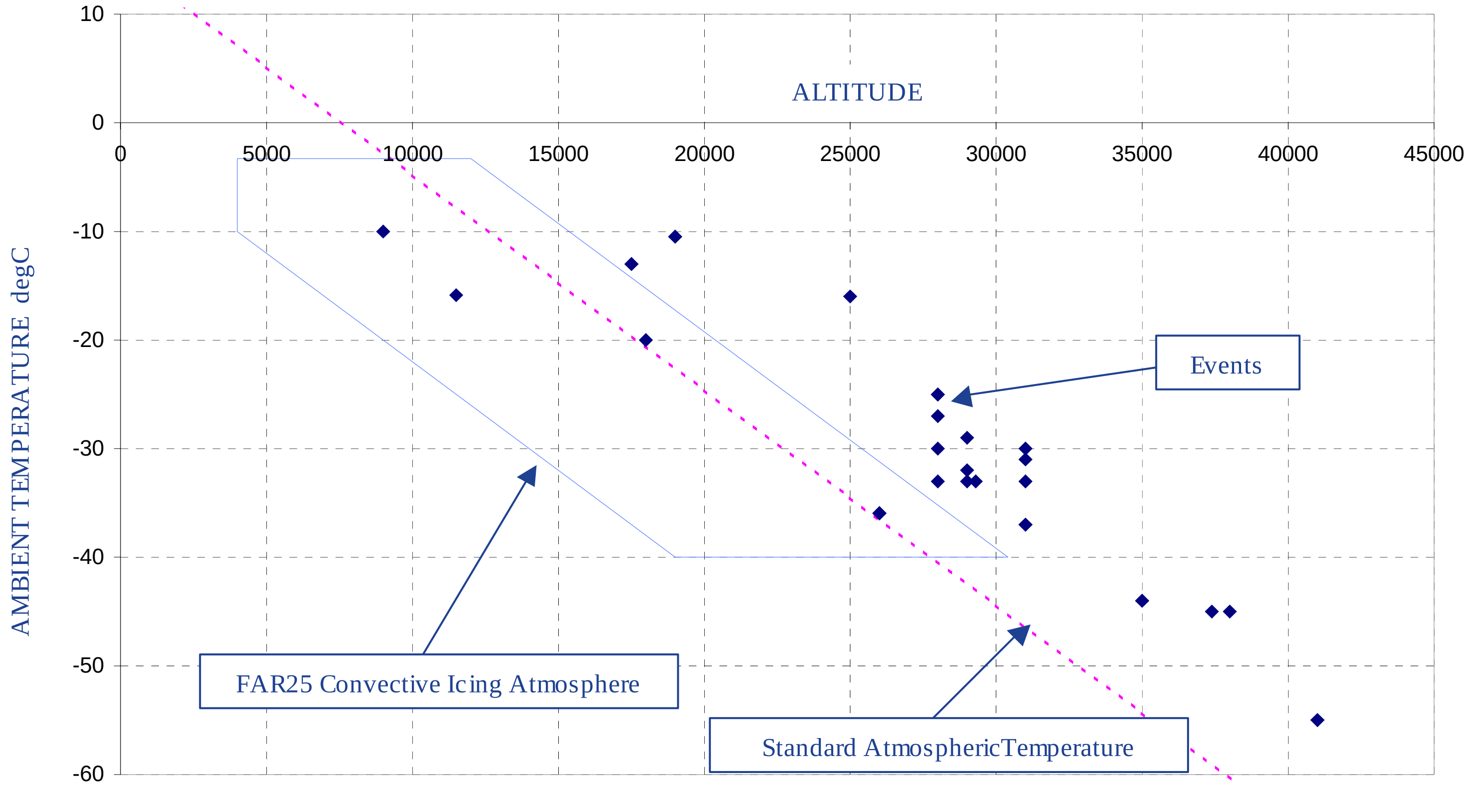
Recent work by rulemaking committee has identified service events which may be due to ice accretion on warm surfaces in glaciated or mixed-phase atmospheres.

This may be of concern for these reasons :

- Ice may form further aft in the engine resulting in effects which may not be seen in current certification testing with super-cooled liquid
- In these atmospheres aircraft surfaces often do not ice, and ice detector systems may not detect, thus engine operating procedures for icing conditions may not be followed resulting in lower margins.

Industry Experience (larger turbofan engines)

Approx. 60 mixed phase / ice crystal related aircraft events in flight from 1989 - 2003 with various symptoms - vibes, flameout, roll-back, surge, airfoil distress



Events with known altitude & Tamb plotted – tend to be ‘hot’ days, high freezing level, Tropical ‘wet’ season

"Theory" of Crystal Icing Mechanism

1. Ice crystals enter engine primary flowpath, upstream surfaces are dry & cooler so no accretion
2. At some point in the turbomachinery, warmer surfaces become wetted due to impacts with crystals and/or liquid
3. Combination of further crystal impacts into wet surface layer and evaporation bring surface to freezing point.
4. Ice begins to form with further crystal impacts.

Note these processes are not fully understood

What's different about MP/G icing ?

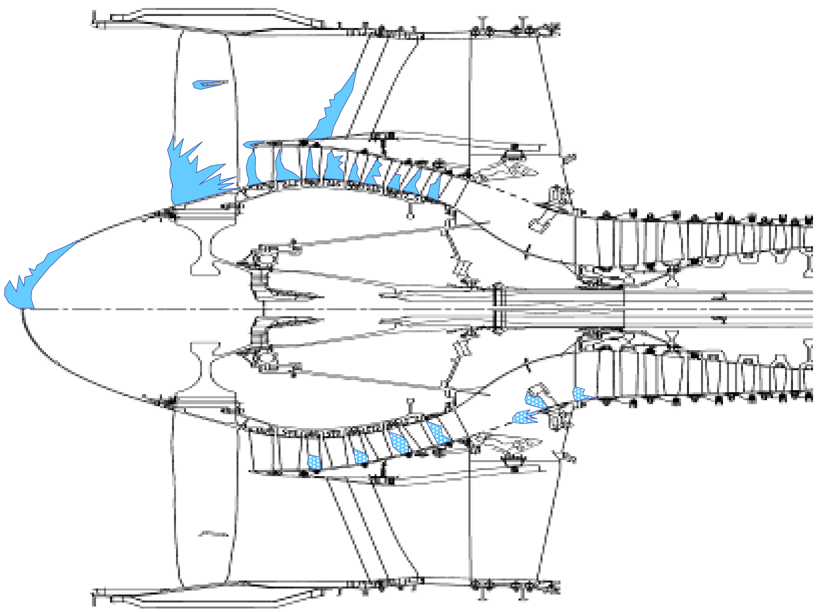
- In a conventional icing environment, super-cooled liquid droplets form rime or glaze ice on the surfaces impacted first.

Super-cooled liquid

Ice Crystals

- In an ice crystal icing environment, theory suggests ice bounces off first surfaces impacted, and accrete on warmer downstream surfaces due to more complex thermodynamic process.

Icing Locations



Questions on Crystal Icing Mechanism

1. Where does liquid come from ?
2. Heat transfer processes ?
3. What type of ice ?
4. Where is icing ‘zone’
5. Shed mechanisms

   Ice interface post-accretion ?

Super-cooled Droplet Icing Atmospheres

FAR25 App C Continuous Maximum Icing Conditions

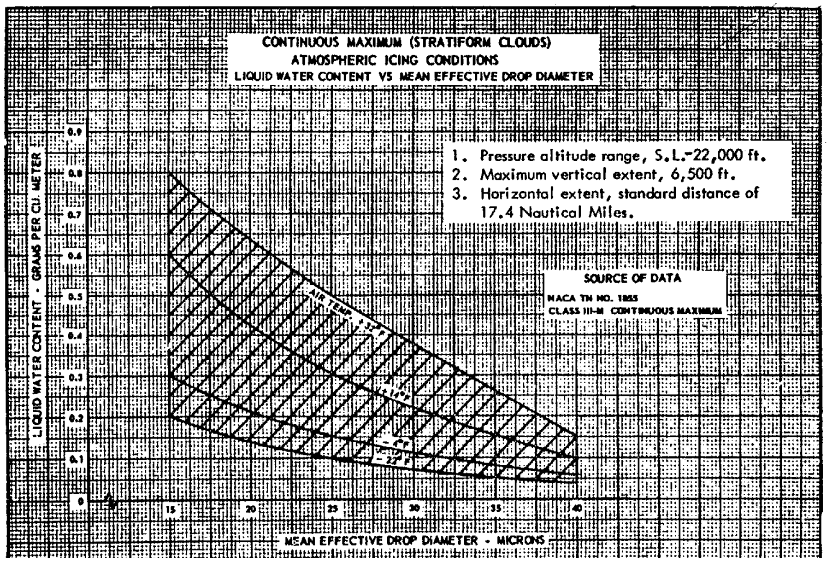


FIGURE 1

Pt. 25, App. C

14 CFR Ch. I (1-1-89 Edition)

FIGURE 3

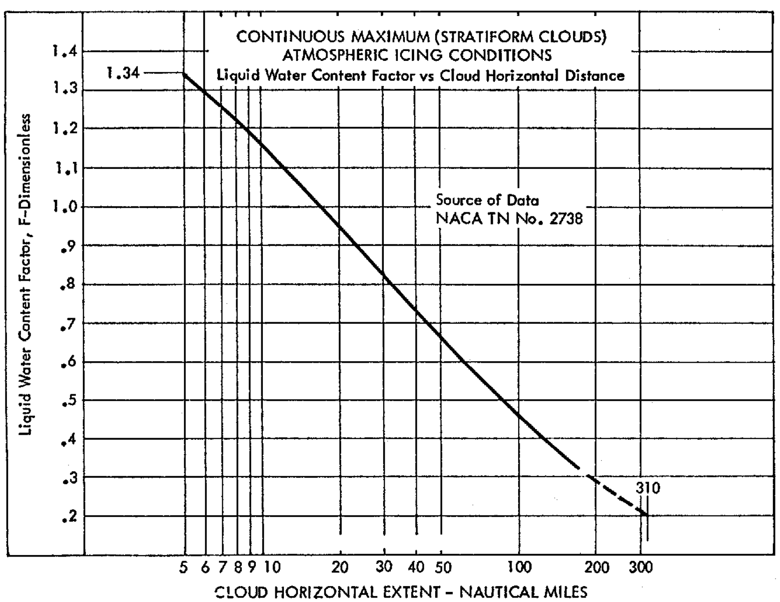
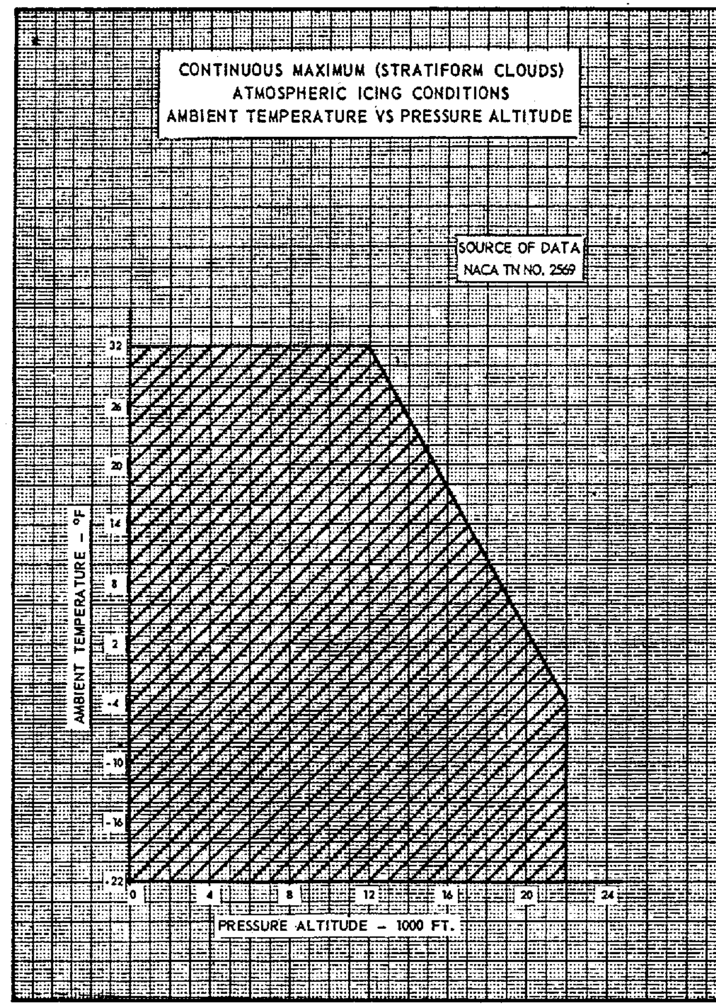


FIGURE 2



FAR25 App C Intermittent Maximum Icing Conditions

FIGURE 4

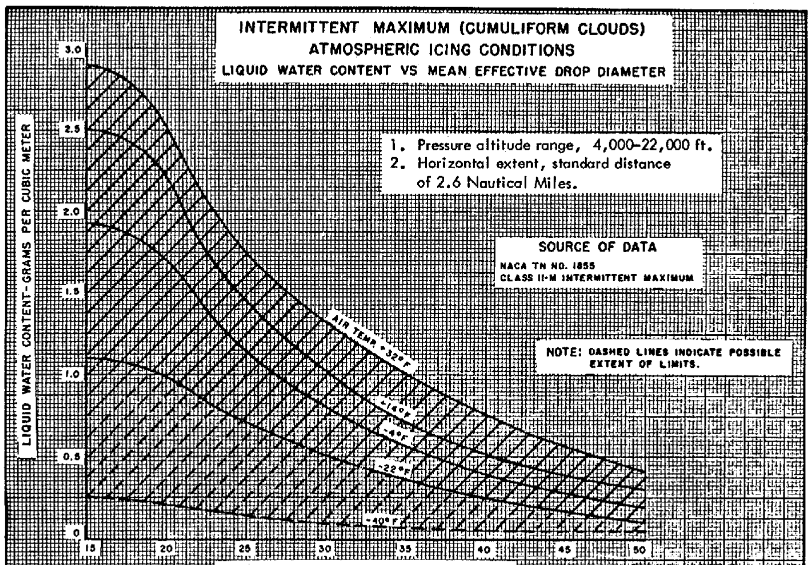


FIGURE 6

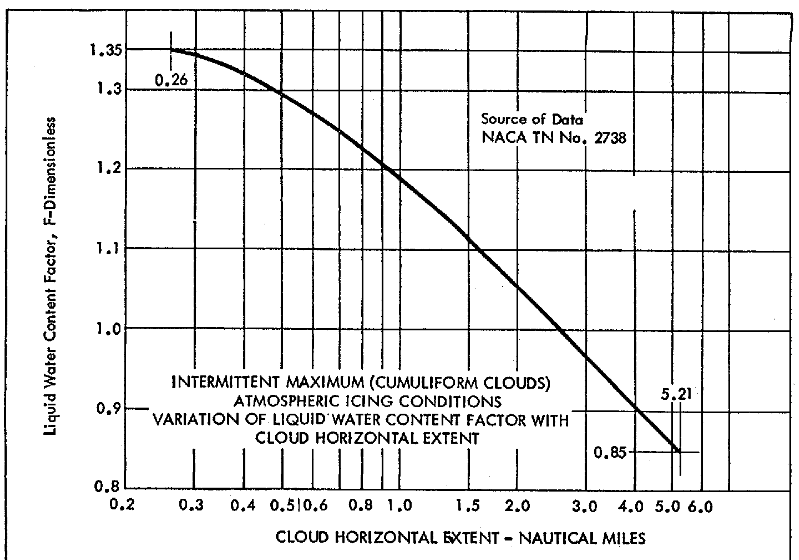
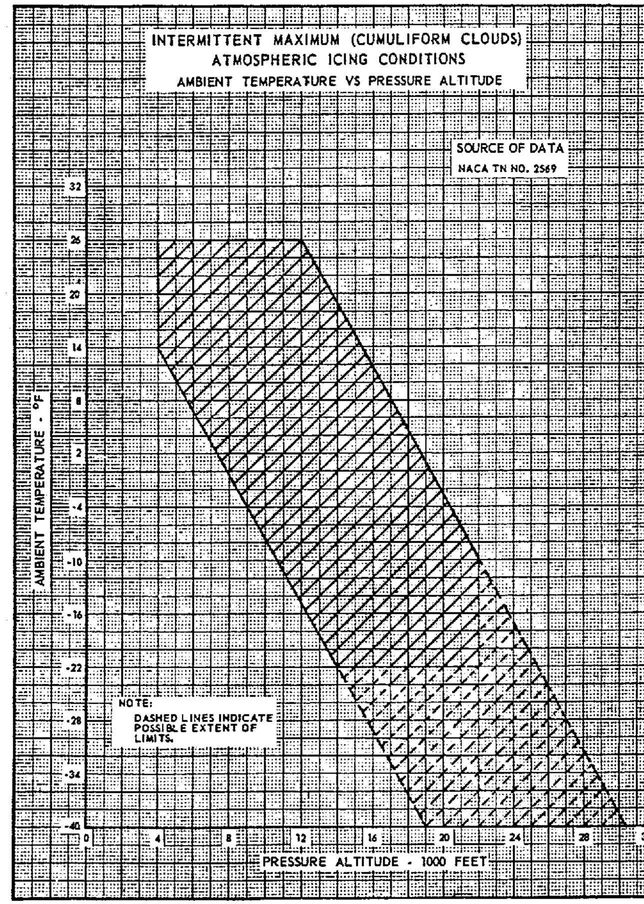
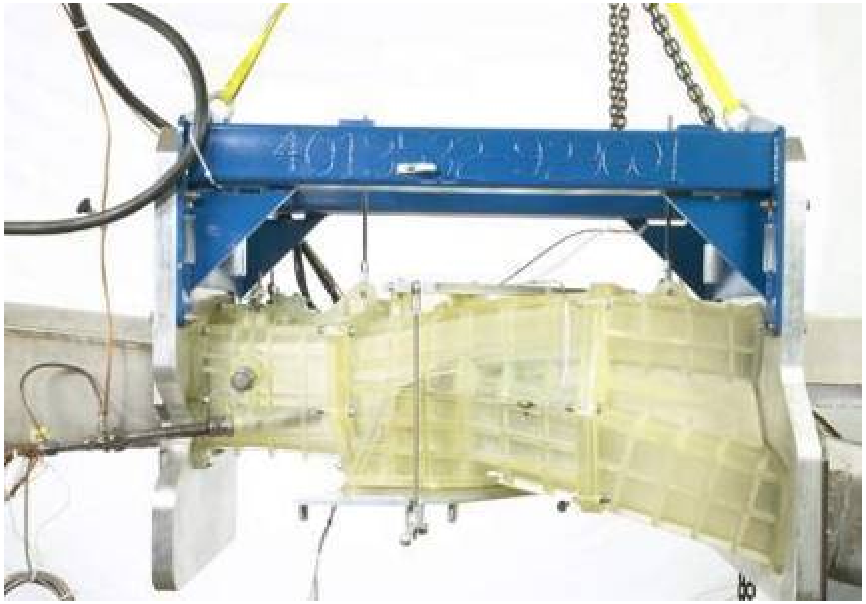


FIGURE 5



Icing Engine Test

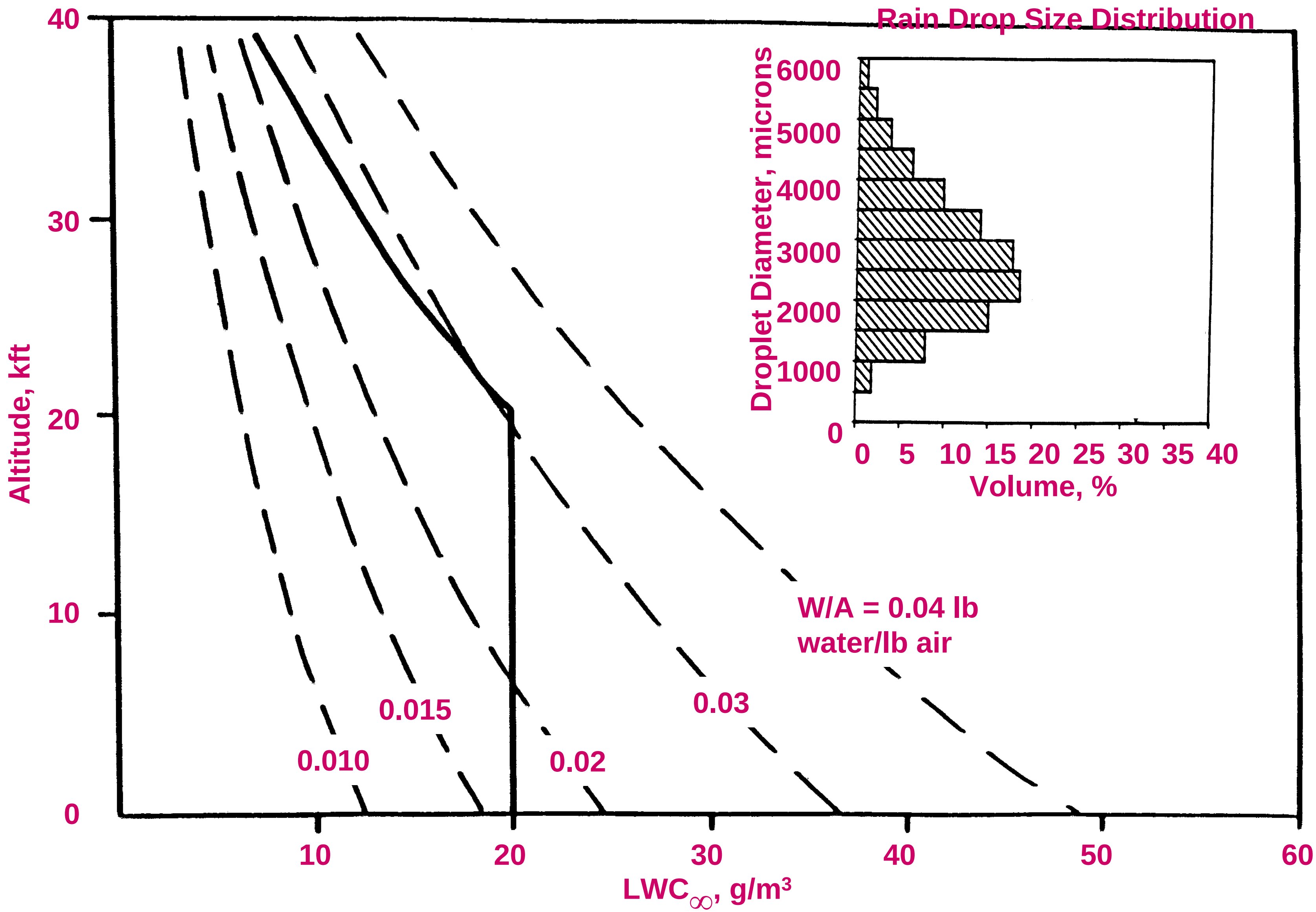


Icing rig test

Super-cooled Droplet Icing

- Complex analyses
  - Whole flight regime & operating envelope
  - Multiple critical points
- Processes reasonably understood
  - Glaze ice accretion uncertainties
  - Shedding uncertainties
- Comprehensive test requirements cover envelope thoroughly

Rain Atmosphere



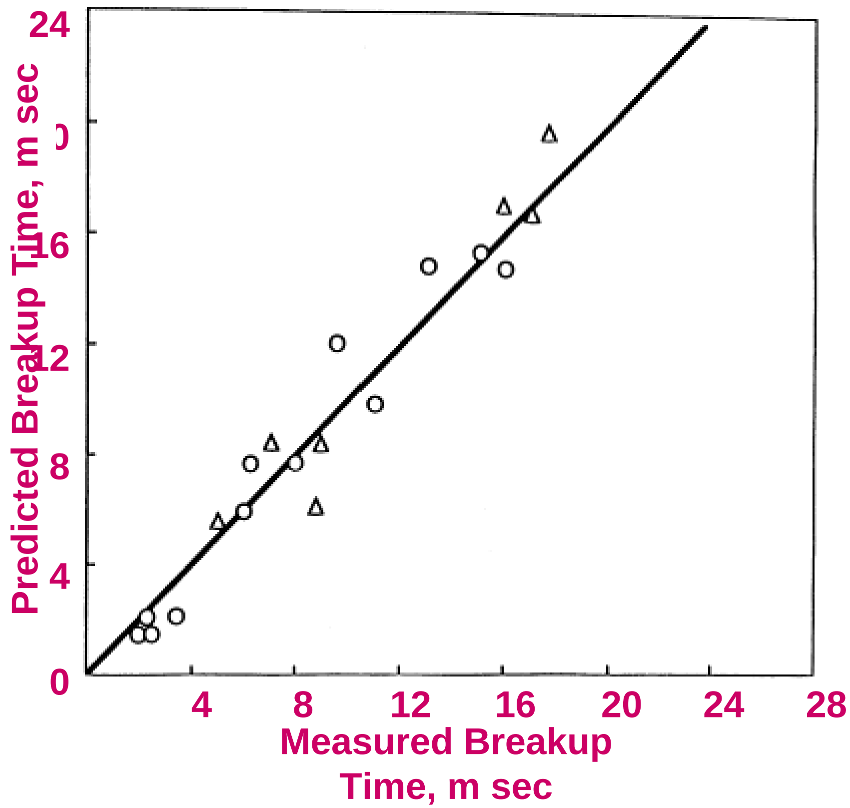
Rain

- Droplets affected by inlet flowfield
  - Break-up due to aero loads
  - Larger droplets impact blading, centrifuged into bypass
  - Smaller droplets are low % of total water

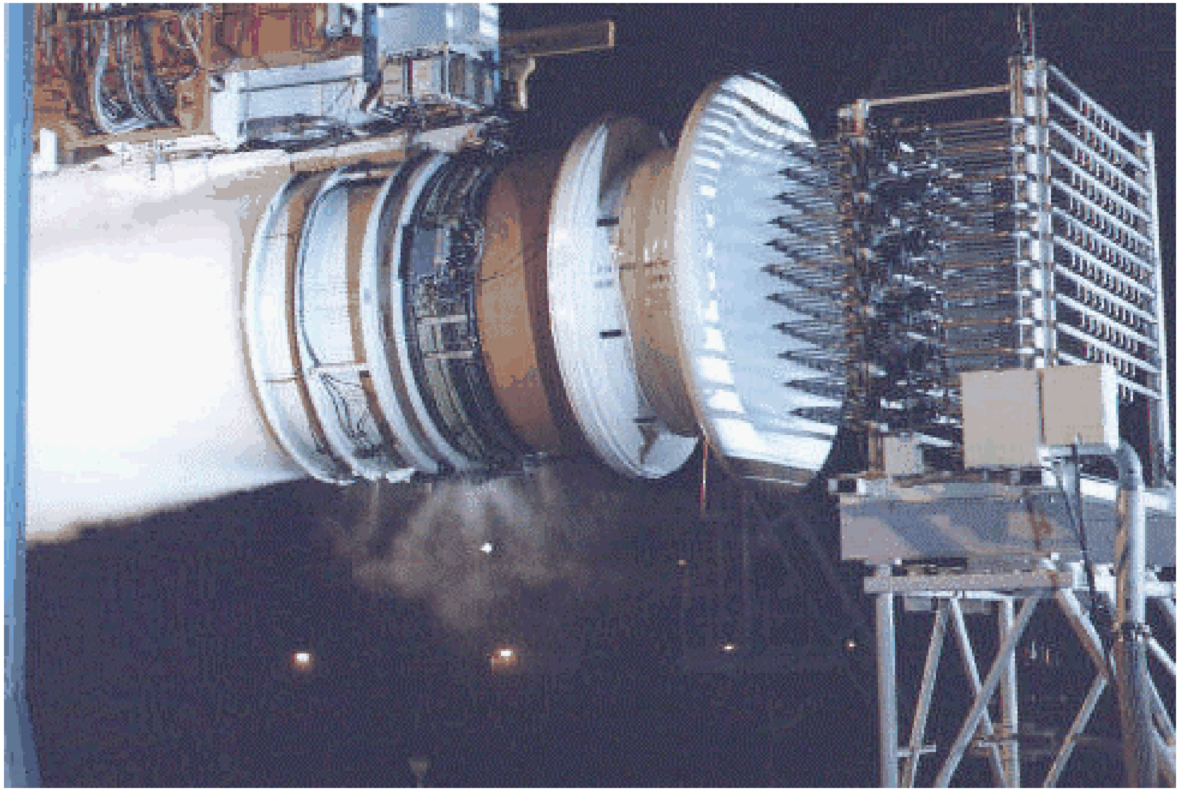
Figure 4.1. Flash Photographs of Water Droplet Breakup in a Steady Stream.
Flattening of the droplet creates a toroidal rim and a hollow bag, the final breakups of which produce large and fine particles, respectively.

Reference: Surveys in Mechanics, Edited by G. K. Batchelor and R.M. Davies, Cambridge University Press, 1956

Droplet Breakup Duration: Measured and Predicted Times



Rain Engine Test



Rain

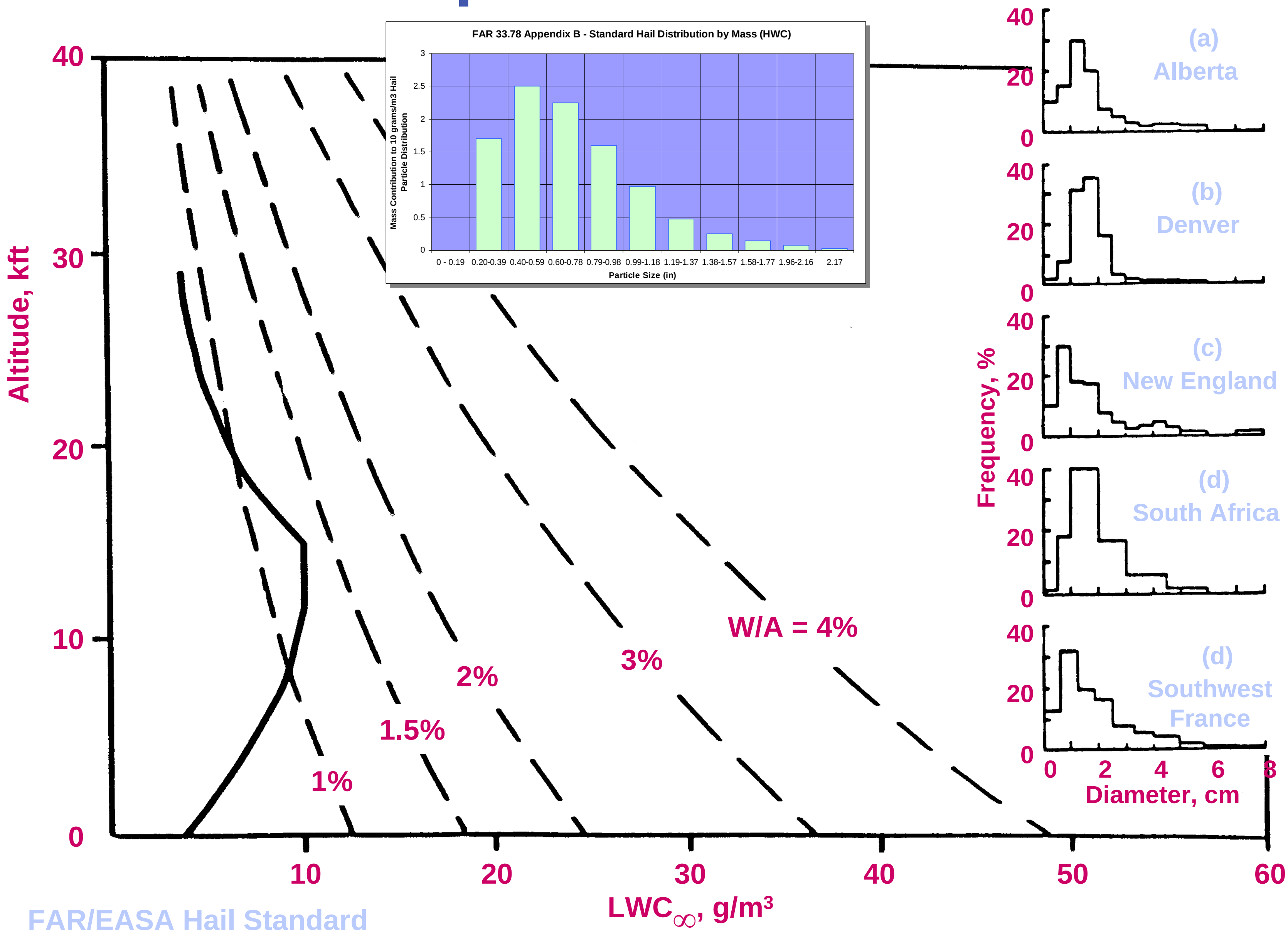
> Relatively complex analysis

> Processes reasonably understood

> Usually benign compared to hail atmosphere

> Above freezing level post-breakup ?
  - Smaller droplets similar to Appendix C icing atmosphere ?
  - Larger droplets SLD ?
  - Potential MP/G ?

Hail Atmosphere



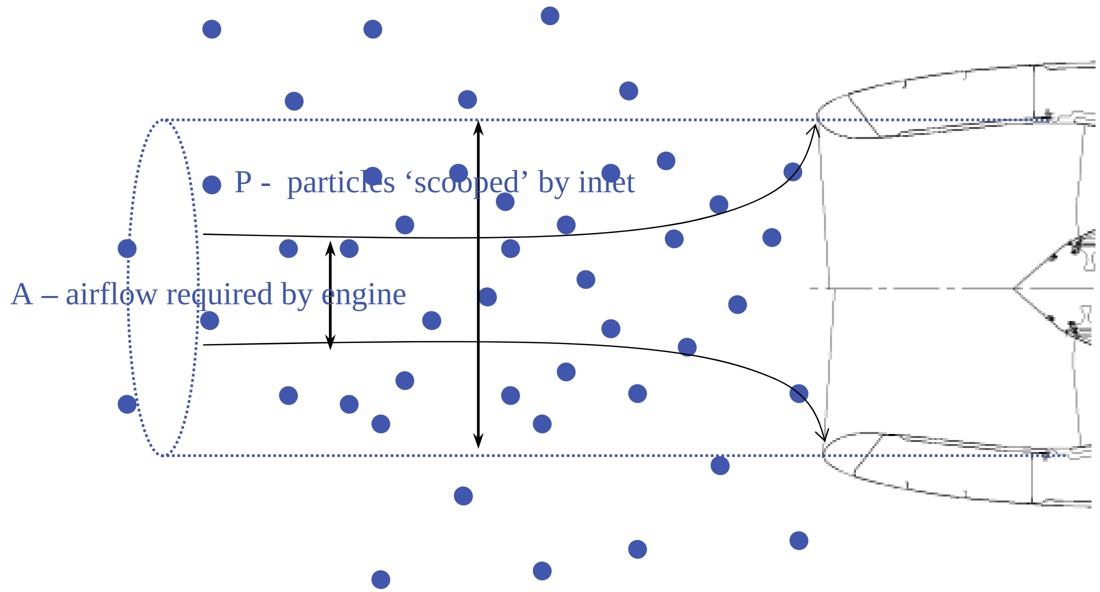
FAR/EASA Hail Standard

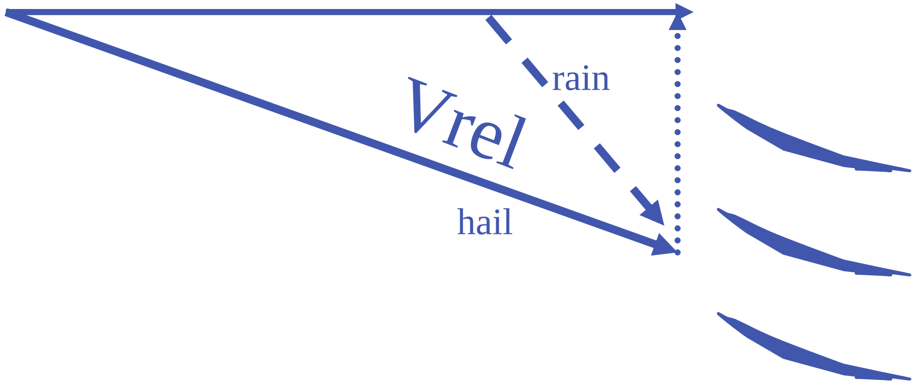
Hail / Graupel

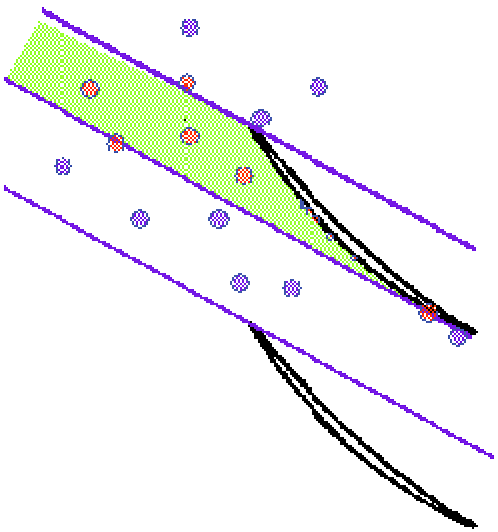
> Inlet flowfield has minor effect on trajectory

> “Scoop factor” and ‘venetian blind’ effects cause hail to be significantly worse threat than rain

Hail / Graupel







Hail Engine Test

Hail

> Simple analysis

> Processes understood

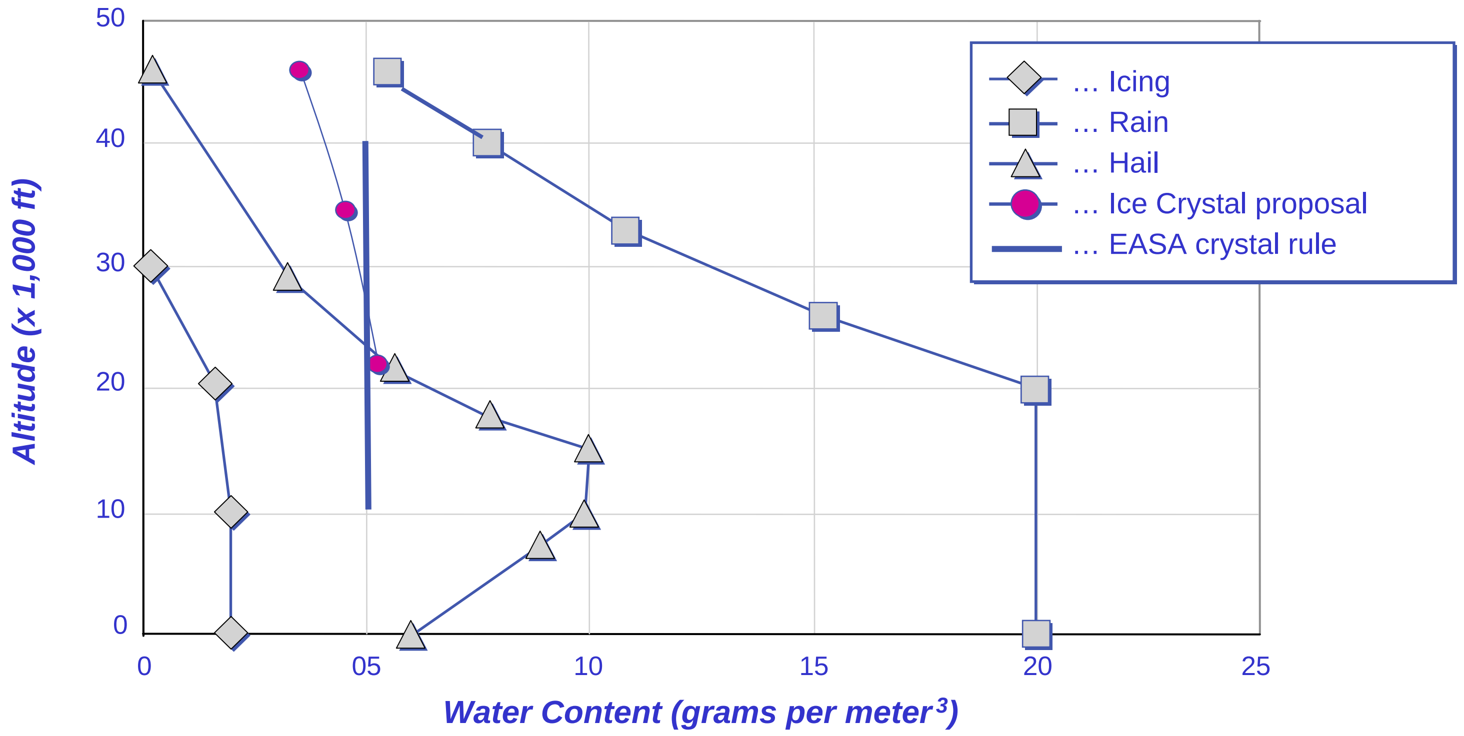
> Most severe atmosphere

> When hail impacts blading it shatters, creating a ‘crystal’ cloud into core?

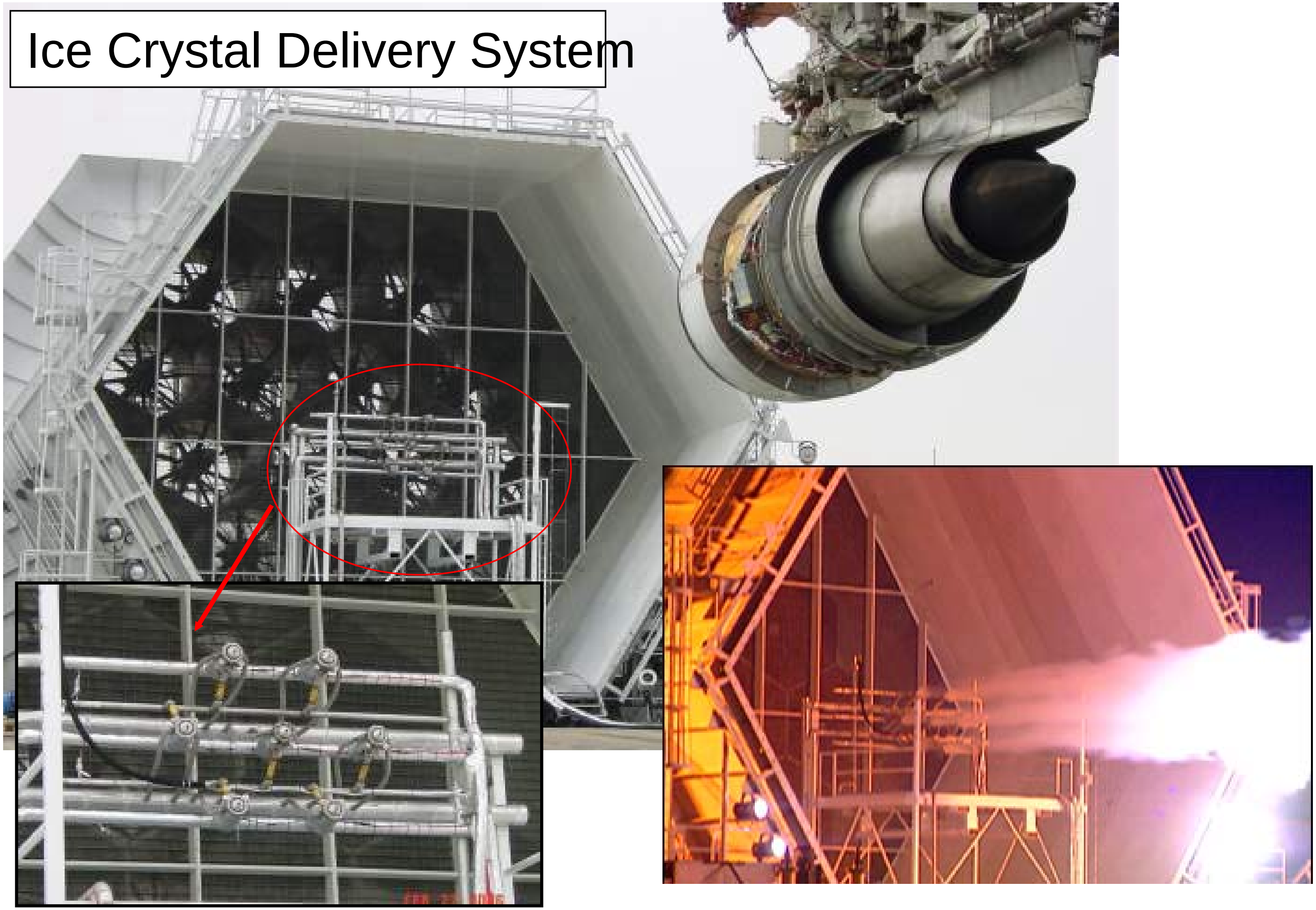
The Service Record

- Current icing regulation has been in use for over 30 years
  - Extensive data from 40's,50's to define atmospheres
  - Industry experience & service/test history using advisory material have defined standard test points which, along with other manufacturer defined 'critical points' appear to have given an excellent service record
- Rain/Hail rule ~15 years
- Recent rulemaking committee (originally SLD) collected event data for 13+ years which included over 200 million flights – relatively few events have occurred.
- New atmosphere for ice crystals may close perceived gaps – but they appear small

Proposed New MP/G Atmosphere



Simulated Ice Crystal Testing



Crystal / Mixed Phase Icing

- Still in infancy
- Fundamental experiments needed to understand the physics of MP/G icing
- Atmosphere uncertain
  - Not just high level crystals ?
- Critical factors uncertain
- Physics of accretion uncertain
- Effect on sensors and control systems uncertain