SUMMARY ~~OF THE INVENTION~~

Foam material is introduced at the gas-path entry of turbine equipment while off-line. The foam will coat and contact the internal surfaces, scrubbing, removing, and carrying fouling material away from equipment.

In an aspect, the present disclosure refers to a method for cleaning a gas turbine engine installed on an airplane, the gas turbine engine having a starter, an open inlet and a compressor, the method comprising: providing a source of a water soluble liquid cleaning agent, a liquid pump, a turbulent mixing chamber, a non-atomizing nozzle and one of an air pump or pressurized gas reservoir; mixing in the mixing chamber pressurized air or gas from the air pump or pressurized gas reservoir with pressurized liquid cleaning agent pressurized by the liquid pump and creating a supply of foam; rotating the gas turbine engine installed on the airplane with the starter; and streaming the supply of foam into the open inlet of the gas turbine engine installed on the airplane from the non-atomizing nozzle as the gas turbine engine is rotating by its starter.

In another aspect, the present disclosure refers to a method for cleaning a gas turbine engine installed on an airplane whilst the gas turbine engine is in a substantially vertical orientation, the gas turbine engine having an inlet and a compressor, the method comprising: providing a source of a water soluble liquid cleaning agent, a liquid pump, an air pump or pressurized gas reservoir, a turbulent mixing chamber, and a non-atomizing nozzle; mixing in the mixing chamber pressurized air or gas from the air pump or pressurized gas reservoir with pressurized liquid cleaning agent pressurized by the

liquid pump and creating a supply of foam; and streaming the supply of foam into the inlet of the installed gas turbine engine from the non-atomizing nozzle.

One ~~aspect of the present invention~~example pertains to an apparatus for foaming a cleaning agent. Some examples ~~embodiments~~ include a housing defining an internal flowpath having first, second, and third flow portions, a gas inlet, a liquid inlet for the cleaning agent, and a foam outlet. The first flow portion includes a gas plenum that is adapted and configured for receiving gas under pressure from the gas inlet and including a plurality of apertures, the plenum and the interior of the housing forming a mixing region that provides a first foam of the liquid and the gas. The second flow portion receives the first foam and flows the first foam past a foam growth matrix adapted and configured to provide surface area for attachment and merging of the cells. The third flow portion flows the second foam through a foam structuring member downstream of either the first portion or the second portion adapted and configured to reduce the size of at least some of the cells. It is understood that yet other examples ~~embodiments of the present invention~~ contemplate a housing having only a first portion; or a first and second portion; or only a first and third portion in various other nucleation devices.

Another example ~~aspect of the present invention~~ pertains to a method for foaming a liquid cleaning agent. Some examples ~~embodiments~~ include mixing the liquid cleaning agent and a pressurized gas to form a first foam. Other examples ~~embodiments~~ include flowing the first foam over a member or matrix and increasing the size of the cells of the first foam to form a second foam. Yet other examples ~~embodiments~~ include flowing the second foam through a

structure such as a mesh or one or more apertured plates and decreasing the size of the cells of the second foam to form a third foam.

Yet another example ~~aspect of the present invention~~ pertains to a system for providing an air-foamed liquid cleaning agent. Other examples ~~embodiments~~ include an air pump or pressurized gas reservoir providing air or gas at pressure higher than ambient pressure, and a liquid pump providing the liquid at pressure. Still other examples ~~embodiments~~ include a nucleation device receiving pressurized air, a liquid inlet receiving pressurized liquid, and a foam outlet, the nucleation device turbulently mixing the pressurized air and the liquid to create a foam. Yet other examples ~~embodiments~~ include a nozzle receiving the foam through a foam conduit, the internal passageways of the nozzle and the conduit being adapted and configured to not increase the turbulence of the foam, the nozzle being adapted and configured to deliver a low velocity stream of foam.

Still another example ~~aspect~~ pertains to a method for providing an air-foamed liquid cleaning agent to the inlet of a jet engine installed on an airplane. Some examples ~~embodiments~~ include providing a source of a pressurized liquid cleaning agent, an air pump, a turbulent mixing chamber, and a non-atomizing supply aperture. Other examples ~~embodiments~~ include mixing pressurized air with pressurized liquid in the mixing chamber and creating a supply of foam. Still other examples ~~embodiments~~ include streaming the supply of foam into the installed engine either through the inlet or through various tubing attached to the engine from the aperture.

Yet another example ~~aspect of the present invention~~ pertains to an apparatus for foaming a water soluble liquid cleaning agent. Some examples ~~embodiments~~ include means for mixing a pressurized gas with a flowing water soluble liquid to create a foam. Other

examples ~~embodiments~~ include means for growing the size of the cells of the foam created by said mixing means and means for reducing the size of the grown cells.

In various examples~~embodiments of the invention~~, the effluent after a cleaning operation is collected and evaluated. This evaluation can include an on-site analysis of the content of the effluent, including whether or not particular metals or compounds are present in the effluent. Based on the results of this evaluation, a decision is made as to whether or not further cleaning is appropriate.

Still further examples ~~embodiments of the present invention~~ pertain to a method in which the effect of a cleaning operation is assessed, and that assessment is used to evaluate the terms of a contract. As one example, the contract may pertain to the terms of the engine warranty provided by the engine manufacturer to the operator or owner of the aircraft. In still further examples ~~embodiments~~ the assessment may be used to evaluate the terms of a contract pertaining to the engine cleaning operation itself. In yet further examples ~~embodiments~~ the assessment of the cleaning effect on the engine may be used to evaluate the engine relative to establish FFA maintenance standards for that engine.

In one example~~embodiment~~, the assessment method includes operating an engine in a commercial flight environment for more than about one month. It is anticipated that in some examples ~~embodiments~~ this operation can include multiple flights per day, and usage of the aircraft for up to seven days per week. The method further includes operating the used engine and establishing a baseline characteristic. In some examples~~embodiments~~, the baseline characteristic can be specific fuel consumption at a particular level of thrust, engine pressure ratio, or rotor speed. In some alternatives, the method includes correcting this baseline data for ambient atmospheric characteristics. In yet other examples~~embodiments~~, the

baseline parameter could be the elapsed time for the start of an engine from zero rpm up to idle speed. In still further examples~~embodiments~~, the baseline assessment of the used engine includes the assessment of engine start time in the following manner: performing a first start of an engine; shutting down the engine; motoring the engine on the starter (without the combustion of fuel) for a predetermined period of time; and after the motoring, performing a second engine start, and using the second engine start time as the baseline start time.

The method further includes cleaning the engine. This cleaning of the engine may include one or more successive cleaning cycles. After the engine is cleaned, the baseline test method is repeated. This second test results (of the cleaned engine) are compared to the baseline test results (of the used engine, as received); and the changes in engine characteristics are assessed against a contractual guarantee. As one example, the operator of the cleaning equipment may have offered contractual terms to the owner or operator of the aircraft with regards to the improvement to be made by the cleaning method. In still further examples~~embodiments~~, the delta improvement provided by the cleaning method (or alternatively, the test results of the cleaned engine considered by itself) can be compared to a contractual guarantee between the manufacturer of the engine (or the facility that performed the previous overhaul of the engine, or the licensee of the engine) to assess whether or not the cleaned engine meets those contractual terms.

In still further examples~~embodiments~~, there is a cleaning method in which a baseline test is performed on a used engine; the engine is cleaned; and the baseline test is performed a

second time. The comparison of the baseline test to the clean engine test can be used for any reason.

In yet other examples~~embodiments~~, the cleaning method includes a procedure in which the engine is operated in a cleaning cycle, and that cleaning cycle (or a different cleaning cycle), is subsequently applied to the engine. Preferably, the cleaning chemicals are provided to the engine at relatively low rotational speeds, and preferably less than about one-half the typical idle speed for that engine.

In still further examples~~embodiments~~, such as in those engines supported substantially vertically, the cleaning chemical can be applied to the engine when the engine is static (i.e., zero rpm). After applying a sufficient amount of chemicals, the engine can then be rotated at any speed, and the cleaning chemicals subsequently flushed.

Yet other examples ~~embodiments of the present invention~~ pertain to methods for cleaning an engine that include manipulation of the temperature of the cleaning chemicals and/or manipulation of the temperature of the engine that is being cleaned. In one example~~embodiment~~, the cleaning system includes a heater that is adapted and configured to heat the cleaning chemicals prior to the creation of a cleaning foam. In still further examples~~embodiments~~, the method includes a heater for heating the air being used to create the foam with the cleaning liquids. In still further examples~~embodiments~~, the cleaning apparatus includes one or more air blowers that provide a source of heated ambient air (similar to "alligator" space heaters used at construction sites). These hot air blowers can be positioned at the inlet of the engine, and the engine can be motored (i.e., rotated on the starter, without combustion of fuel) for either a predetermined period of time (which may be based on ambient conditions), or motored until thermocouples or other temperature

measurement devices in the engine hot section have reached a predetermined temperature. In still further examples~~embodiments~~, the temperature of the engine prior to the introduction of the cleaning foam can be raised by starting the engine and operating the engine at idle conditions for a predetermined period of time, and subsequently shut down the engine prior to introduction of the cleaning foam. In still further examples~~embodiments~~, the engine can be motored after the shutdown from idle and before the introduction of chemicals to further achieve a consistent baseline temperature condition prior to introduction of the foam. Still further examples ~~embodiments of the present invention~~ contemplate any combination of preheated liquid chemicals, preheated compressed air used for foaming, externally heated engines, and engines made "warm" by one or more recent periods of operation.

In still further examples~~embodiments of the present invention~~, the cleaning foam can be heated by providing a heating element within the device used to mix and create the cleaning foam.

It will be appreciated that the various apparatus and methods described in this summary section, as well as elsewhere in this application, can be expressed as a large number of different combinations and subcombinations. All such useful, novel, and inventive combinations and subcombinations are contemplated herein, it being recognized that the explicit expression of each of these combinations is unnecessary.

WHAT IS CLAIMED IS:

1. A method for ~~scheduling a foam~~ cleaning ~~of~~ a gas turbine~~,~~ engine (10) installed on an airplane, the gas turbine engine (10) having a starter, an open inlet (11) and a compressor (13), the method comprising:

providing a source of a water soluble liquid cleaning agent, a liquid pump, a turbulent mixing chamber, a non-atomizing nozzle (30) and one of an air pump or pressurized gas reservoir;

mixing in the mixing chamber pressurized air or gas from the air pump or pressurized gas reservoir with pressurized liquid cleaning agent pressurized by the liquid pump and creating a supply of foam;

rotating the gas turbine engine (10) installed on the airplane with the starter; and

streaming the supply of foam into the open inlet (11) of the gas turbine engine (10) installed on the airplane from the non-atomizing nozzle (30) as the gas turbine engine (10) is rotating by its starter.

2. The method of claim 1, wherein the gas turbine engine includes a combustor, and which further comprises cleaning the combustor with foam streamed into the inlet.

3. The method of claim 1, wherein the gas turbine engine (10) is rotated at a speed of between 25% and 75% of its maximum engine motoring speed.

4. The method of claim 1 wherein the streamed supply is at a velocity greater than 0.91 metres per second (three feet per second) and less than 4.5 metres per second (fifteen feet per second).

5. The method of any of the preceding claims, wherein the streamed supply is a unitary stream of substantially constant diameter.

6. The method of any of the preceding claims, further comprising providing a cell growth chamber downstream of the mixing chamber and growing the size of the foam cells after said mixing and before said streaming.

7. The method of any of the preceding claims, further comprising providing a turbulence-reducing chamber downstream of the mixing chamber and reducing the turbulence of the mixed foam after said mixing and before said streaming.

8. The method of any of the preceding claims, further comprising:

rotating all spools of the gas turbine engine (10) during said streaming;

permitting an innermost spool to come to a stop and maintaining said streaming after the innermost spool has stopped; and

rerotating all spools of the gas turbine engine (10) after the innermost spool has stopped.

9. The method of any of the preceding claims, wherein said nozzle (30) is adapted and configured to provide the stream of foam to one of a bleed air duct of the gas turbine engine (10) or to a manifold of tubing mounted to the gas turbine engine (10).

10. The method of any of the preceding claims, wherein said mixing includes flowing the liquid in a first direction and injecting the gas in a second direction that has a velocity component at least partly opposite to the first direction.

11. The method of any of the preceding claims, wherein the air received by said mixing chamber has a pressure more than 68.9 kilopascals (ten psig) and less than 827 kilopascals (one hundred and twenty psig), and the liquid received by said mixing chamber has a pressure more than 68.9 kilopascals (ten psig) and less than 827 kilopascals (one hundred and twenty psig).

12. The method of any of the preceding claims, wherein said mixing chamber includes an air-pressurized plenum having a plurality of airflow apertures and located within a chamber provided with a flow of the liquid, the apertures expelling air into the flowing liquid to create the foam.

13. The method of any of the preceding claims, wherein mixing in the mixing chamber comprises mixing the liquid cleaning agent and pressurized gas to form a first foam, said creating a supply of foam comprising flowing the first foam

over a member or matrix and increasing the size of the cells of the first foam to form a second foam.

14. The method of claim 13, wherein said creating a supply of foam further comprises flowing the second foam through a structure, such as a mesh or one or more apertured plates, and decreasing the size of the cells of the second foam to form a third foam.

15. A method for cleaning a gas turbine engine (10) installed on an airplane whilst the gas turbine engine (10) is in a substantially vertical orientation, the gas turbine engine having an inlet (11) and a compressor (13), the method comprising:

providing a source of a water soluble liquid cleaning agent, a liquid pump, an air pump or pressurized gas reservoir, a turbulent mixing chamber, and a non-atomizing nozzle (30);

mixing in the mixing chamber pressurized air or gas from the air pump or pressurized gas reservoir with pressurized liquid cleaning agent pressurized by the liquid pump and creating a supply of foam; and

streaming the supply of foam into the inlet of the installed gas turbine engine (10) from the non-atomizing nozzle (30).

16. The method of claim 15, wherein the gas turbine engine (10) comprises a starter, the method comprising rotating the installed gas turbine engine (10) with

the starter after streaming a sufficient amount of foam, and subsequently flushing the cleaning agent.

17. The method of any of the preceding claims, further comprising:

quantifying a range of improvement to an operational parameter of a family of gas turbine engines (10) achievable by foam washing ~~of~~ a member of the family;

~~———~~operating a specific engine (10) of the family installed on an aircraft for a period of time;

~~———~~measuring the performance of the specific engine (10) during said operating;

~~———~~determining that the specific engine (10) should be foam washed; and

~~———~~scheduling a foam ~~cleaning~~washing of the specific engine~~.~~ (10).

18. The method of claim 17

~~2. The method of claim 1 which further comprises providing the measured performance of the specific engine to the owner of the engine, and said determining is by the engine owner.~~

~~3. The method of claim 1~~ wherein the operational parameter is ~~the~~a start time or a~~.~~

~~4. The method of claim 1 wherein the operational parameter is the~~ specific fuel consumption of the ~~engine.~~

gas turbine

5. The method of claim 1 wherein the operational parameter is the carbon emitted by the engine.

6. The method of claim 1 wherein the specific engine is installed on an aircraft and said measuring is while flying.

7. The method of claim 1 which further comprises:

operating a source of a liquid cleaning agent, a liquid pump, and a source of pressurized gas;

mixing pressurized gas with pressurized liquid and creating a supply of foam; and

streaming the supply of foam into the specific engine.

8. The method of claim 7 wherein said determining is based on one of carbon emissions or oxides of nitrogen emissions.

9. The method of claim 1 wherein said determining is by comparing said measuring to a predetermined range of improvement achievable by foam washing to the performance of the engine.

10. The method of claim 7 wherein said determining is based on one of carbon emissions or oxides of nitrogen emissions.

~~11. The method of claim 1 wherein said operating includes commercial passenger flight operation and which further comprises providing the measured performance by telemetry.~~

~~12. The method of claim 10 wherein said scheduling a foam washing of the specific engine is by a data center, and said streaming is into the inlet of the specific engine.~~

~~13. The method of claim 12 wherein said determining is based on one of carbon emissions or oxides of nitrogen emissions.~~

~~14. The method of claim 10 wherein said operating is commercial passenger operation of the specific engine for a period of time, and said measuring is during the period.~~

~~15. The method of claim 10 wherein said determining is by the owner of the engine.~~

~~16. The method of claim 10 wherein said determining is by the operator of the engine.~~

~~17. The method of claim 9 wherein said measuring is of start time.~~

~~18. The method of claim 9 wherein said measuring is of fuel consumption.~~

~~19. The method of claim 9 wherein said measuring is of rotor speed.~~

~~20. The method of claim 9 wherein said measuring is of engine pressure ratio.~~

~~21. The method of claim 9 wherein said measuring is of turbine temperature required to achieve a particular power output.~~

~~22. The method of claim 9 wherein the specific engine is installed on an aircraft and said measuring is of the operating speed of the engine when the aircraft is at cruise.~~

~~23. A method for providing a gas-foamed liquid cleaning agent to a gas turbine engine:~~

~~operating a gas turbine engine installed on an aircraft;~~

~~measuring the performance of the~~ engine ~~during said operating;~~(10).

~~determining that the engine should be foam washed based on said measuring;~~

~~operating a source of a liquid cleaning agent, a liquid pump, and a source of pressurized gas;~~

~~mixing pressurized gas with pressurized liquid and creating a supply of foam; and~~

~~streaming the supply of foam into the engine.~~

~~24. The method of claim 23 wherein said determining is based on one of carbon emissions or oxides of nitrogen emissions.~~

~~25. The method of claim 23 wherein said determining is by comparing said measuring to a predetermined range of improvement achievable by foam washing to the performance of the engine.~~

~~26. The method of claim 25 wherein said determining is based on one of carbon emissions or oxides of nitrogen emissions.~~

~~27. The method of claim 25 which further comprises providing the measured performance by telemetry to a data center.~~

~~28. The method of claim 27 which further comprises scheduling a foam washing of the engine by the data center.~~

~~29. The method of claim 28 wherein said determining is based on one of carbon emissions or oxides of nitrogen emissions.~~

~~30. The method of claim 27 wherein said operating is commercially operating the engine for a period of time, and said measuring is during the period.~~

~~31. The method of claim 27 wherein said determining is by the owner of the engine.~~

~~32. The method of claim 27 wherein said determining is by the operator of the engine.~~

~~33. The method of claim 25 wherein said measuring is of start time.~~

~~34. The method of claim 25 wherein said measuring is of fuel consumption.~~

~~35. The method of claim 25 wherein said measuring is of rotor speed.~~

~~36. The method of claim 25 wherein said measuring is of engine pressure ratio.~~

~~37. The method of claim 25 wherein said measuring is of turbine temperature required to achieve a particular power output.~~

~~38. The method of claim 25 wherein said measuring is of operating speed of the engine at cruise.~~

~~39. The method of claim 25 wherein the measured performance is provided by telemetry, and which further comprises scheduling a foam washing of the engine.~~

~~40. The method of claim 39 wherein said measuring includes one of start time, fuel consumption, rotor speed, engine pressure ratio, turbine temperature required to achieve a particular power output, or operating speed of the engine at cruise.~~