Application of Fault-Tree Analysis to Troubleshooting the NASA GRC Icing Research Tunnel

Edward J. Zampino • Aerospace Engineer • NASA Glenn Research Center (GRC)

Key Words: Corrective Action, Failure, Failure Cause Determination, Faults, Functions, Reliability Improvement, Team approach, Training

SUMMARY & CONCLUSIONS

In 1997, the NASA Glenn Research Center in Cleveland Ohio conducted an extensive troubleshooting effort on its Icing Research Wind Tunnel (known as the IRT). This effort utilized fault tree analysis as an analytical troubleshooting tool in order to "attack" a serious non-repeatability problem with IRT icing cloud parameters. A team of knowledgeable managers, engineers, and technicians was formed to conduct the analysis. The construction of the IRT fault tree created a "picture" of the causal structure of potential faults that could contribute to the existence of a non-repeatability problem. The analysis team investigated many problem areas that were indicated by the fault tree. The Fault Tree Analysis was an important aid in the troubleshooting effort which pulled in organizations needed to investigate the problem and caused a number of simultaneous corrective actions to occur. These actions were critical in restoring the repeatability of the icing cloud parameters even though no single root cause of the problem could be identified. In addition, the analysis team found 9 system level considerations which were brought forward to improve tunnel operations. The possibility of implementing the recommendations was investigated by the IRT staff. It was found that many of the recommendations had already been a matter of practice for quite a long time, but others were not and were selected for implementation.

We learned that the effectiveness of the analysis was greatly enhanced by a team approach, and by a critical team review of all fault tree sections constructed. Personnel investigated the possibility that certain fault events could exist even when it appeared that the likelihood of an event was small. Intermediate events or potential primary faults were not removed from the fault tree unless sufficient evidence was presented to do so. The IRT management also realized that the fault tree analysis report provided a baseline and history for the investigation of this non-repeatability problem. If it was to re-occur, NASA Glenn Research Center would have an analytical record of the procedure followed to solve the problem and would not have to re-start from "ground zero." It was learned that fault tree analysis is certainly a valuable tool for the troubleshooting of a complex facility.

1. INTRODUCTION

The Icing Research Tunnel (IRT) is GRC's oldest and busiest facility. Built at the end of World War II, the IRT was instrumental in developing and testing ice protection systems for piston and propeller-driven aircraft. Since that time, the IRT has been updated with a larger fan motor, improved fan blades, computerized tunnel controls, and electronic data acquisition, storage, and processing.

The IRT has played a substantial role in developing, testing, and certifying methods to prevent ice buildup on gas-turbine-powered aircraft. Work continues today in the investigation of low-power electromechanical deicing and anti-icing fluids for use on the ground, deicing and anti-icing research on STOVL rotor systems and certification of ice protection systems for military and commercial aircraft. [1]

1.1 GLOSSARY

- Component: A combination of parts, devices, or structures which performs a distinctive action, process, or provides support.
- System: The totality of components, software, and humans which, when working together in a successful manner, will carry out the various tasks to achieve experiment success.
- Subsystem: A set of components, command signals, and human initiated actions which carry out a specialized set of Icing Research Tunnel system tasks. (example: subsystem for air cooling)
- Event: A change of state in system parameters or processes which may or may not be directly detectable but could affect the functional output of the system.
- Function: An action or process performed by a sub-system or component, which usually involves the transfer of energy and may include the transfer of information. [Note: an alternative definition may apply to passive components of a system such as structure whose "function" is load bearing capability. Welds, brazings, and epoxy have a function which is to provide adhesion of parts when subjected to forces. "Function" applies to water and air in that their function is to provide consumable products required to create the Icing wind tunnel cloud.]
- Top Level Event: An undesired state of a system caused by events occurring within the system or in the system environment.
- Intermediate Events: Events which either alone or in combination with other events are necessary and sufficient to cause the Top Level Event, but are complex: They are caused by basic events (component failures or faults) which can occur either alone or in combination. (Example: Non-repeatability of air cooling subsystem would be a intermediate event leading to non-repeatability of the icing cloud because "Non-repeatability of air cooling" is caused by a set of specific failures or faults)
- Fault: An event which either alone or in combination with other events will contribute to the existence of a particular undesired state of a system.

- Failure: The inability of a system, subsystem, component or part to perform its required function within specified limits, under specified conditions for a specified duration.
- Basic Event: A basic event represents a fault such as hardware failure, human error, or an adverse condition. The basic events are symbolized using a circle which signifies that the fault does not require further development. An alternate symbol for a basic event is a boxed basic event that provides a box to contain the description of the basic event.
- Undeveloped Event: The undeveloped event is a complex event that has not been further developed by fault tree logic. A diamond symbol is used in order to denote an undeveloped event.
- Escort-D subsystem: A mini-computer based, real time, data acquisition system which is interactive and can collect, process, display, and record data as accumulated during a test.
- Turntable: A circular table in the IRT test section to which aero-dynamical models can be attached by means of a mounting plate. The turntable can be rotated $\pm$ 20° in the horizontal plane with respect to the tunnel wind velocity in the test section.

2. SYSTEM DESIGN AND OPERATION

The Icing Research Tunnel (IRT) is capable of achieving an airspeed of 50 to 430 mph. in its empty test section and by controlling liquid water content, droplet size, and temperature, it can duplicate the icing conditions encountered by aircraft. The test section of the tunnel is 6 ft high, 9 ft. wide, and about 20 ft long. Typically, aerodynamic models are set up in the test section to study the formation of ice on structures or components and determine methods for protection from ice build-up. To duplicate the aircraft icing environment, the IRT contains a heat exchanger and refrigeration plant to achieve desired temperatures and a spray system to generate a cloud of microscopic, super-cooled droplets of water. [2] In Figure 1 below is a top view of the Icing Research Tunnel, shop, and control room sections of the IRT building as it existed at the time of the analysis. [3]

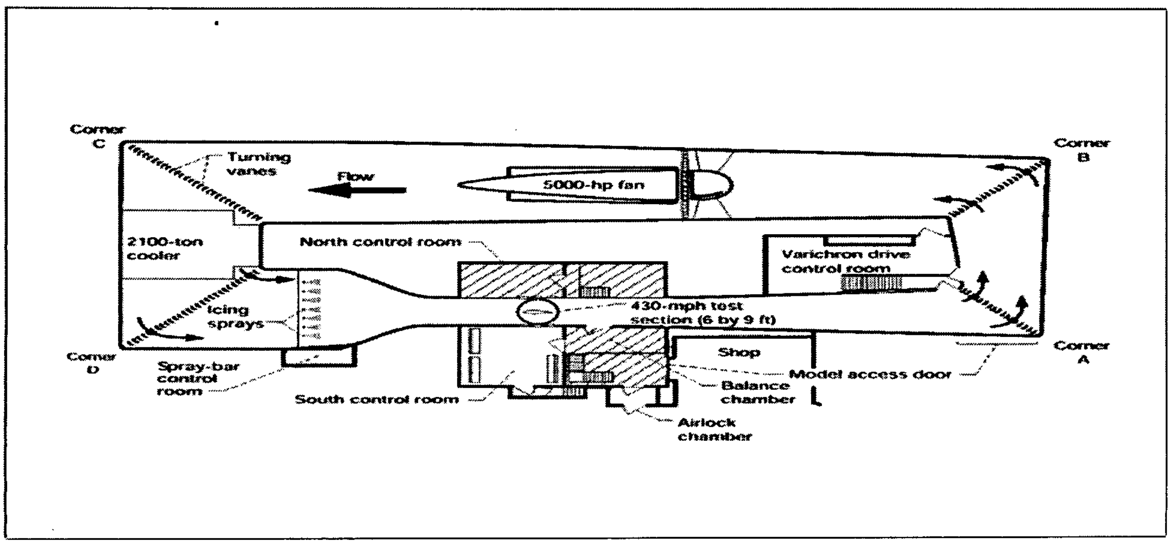

Figure1 (Top view of the IRT)

1.2 ACRONYMS

The following are acronyms:
IRT – Icing Research Tunnel
GRC – Glenn Research Center
Psia – Pounds per square inch absolute. (pressure)
STOVL – Short take off and Vertical Landing
WDPF – Westinghouse Distributed Processing Family (a distributed control system)

The large balance chamber that surrounds the test section in Figure 1 above, is at approximately the same static pressure as the test section; therefore, no pressure bulkhead fittings or hermetically sealed connections are needed for the instrumentation leads and service air hoses entering the tunnel test-section ceiling and floor. Personnel access to the test section from the balance chamber is through a 4.5 ft. wide by 5.25 ft. high door in the south tunnel wall. The major components of the main drive system are the fan motor, the fan blades, and the fan inlet guide vanes. The variable-speed motor (which is air cooled and rated at 5000 hp) is installed inside the faired nacelle. It is controlled from the operator's console in the control room. From this console, the drive motor can be started and stopped and the motor speed can be adjusted throughout a given tunnel experiment. The main drive motor is directly coupled to a fixed pitch, 12 bladed fan fabricated from laminated Sitka spruce. The fan has a diameter of 25.17 ft., and its maximum rotational speed is 460 revolutions per minute. Air assisted water spray nozzles are used to produce the proper sized droplets in the icing cloud. Ten spray bar assemblies with a total of approximately 130 nozzles produce a nearly uniform icing cloud in the tunnel test section. Standard or modified nozzles can be installed in the spray bars; and, essentially the only difference between them is the diameter of the nozzle water tube.

The tunnel is operated from an interactive, distributive control system known as the WDPF (Westinghouse Distributed Processing Family). Two operator's consoles have color graphic displays for setting and monitoring the facility's operation. From these consoles, tunnel fan speed, spray bar air and water pressures, spray duration, experiment turntable position, and other auxiliary systems are controlled. A third console contains instrumentation displays that are used to control tunnel lighting, fan low-speed lockout, and emergency shut down. The facility instrumentation necessary to operate the tunnel is normally displayed on the WDPF graphics pages. Data such as tunnel air velocity, motor revolutions per minute, average tunnel temperature, model angle-of-attack, spray-bar control parameters, and other auxiliary systems information are primarily monitored by the tunnel operators.

Facility temperatures are measured at all four corners of the tunnel. Corner D of the tunnel (see Fig. 1) has 11 type-T thermocouples whose readings are mathematically averaged to represent the air temperature in the test section. Each spray bar is also instrumented with thermocouples to measure both air and water temperatures. These facility temperatures are displayed on the WDPF system.

Two facility pitot tubes measure total pressure with a 0-to-15 psia transducer and measure total-minus-static pressure with a 0-to-3.0 psi differential pressure transducer. These pressure measurements are input to the WDPF and Escort-D systems and, together with the test section temperature, are used to calculate tunnel wind velocity. The facility spray bar air pressure and water-minus-air differential pressure are displayed on the WDPF and the Escort D data systems.
The refrigeration heat exchanger is located downstream of the tunnel drive fan and upstream of the spray nozzles. The spray nozzles are upstream of tunnel test section. There are unheated turning vanes upstream and downstream of the heat exchanger. The refrigeration heat exchanger has eight identical heat exchanger units, each spanning the 8.8m (29ft) wide IRT duct. It has also been folded to fit in the IRT and to have enough area to cool the air flow sufficiently. The sheet metal turning vanes on the downstream face of the heat exchanger provide a straightening of the air flow and keep the pressure drop low.

3. THE PROBLEM

In June and July of 1997, anomalies were observed in the IRT data. The IRT staff decided to "move up" the usual periodic calibration check on tunnel operation and verified that there was a non-repeatability of icing cloud parameters. Customers were notified about the anomalies and it was determined that the non-repeatability of the icing cloud parameters had not adversely affected the scientific value of the data collected. However, the non-repeatability of the icing cloud could not be tolerated. The day-to-day variation in cloud uniformity might eventually affect the value of scientific data for specific types of tests. Basically, measurements of the icing cloud uniformity are made by measuring the ice layer thickness on various calibration surfaces of a metal calibration grid that is located in the test section of the tunnel. The icing cloud uniformity had shifted from its previous full calibration in March of 1997 and was non-repeatable not only from one day of operation to the next but even from spray-to-spray. A number of attempts were made to correct this problem but were unsuccessful. The IRT manager, engineers, technicians, and Office of Safety and Assurance Technologies formed a troubleshooting team whose job was to perform a disciplined, systematic and analytical approach to the troubleshooting activity. Following some discussion, fault tree analysis [4, 5, 6, 7] was chosen as the analytical tool to guide and control the investigation.

4.THE FAULT TREE ANALYSIS PLAN

One of the most important tasks to be performed early on was to familiarize members of the team with the methodology of fault trees. A short, informal tutorial session with some "handout" materials was provided. Team members quickly grasped the overall concepts. The tutorial was deliberately kept as simple as possible so as to encompass the construction of fault trees: the top level event, intermediate events, basic fault events, and logic gates. Topics such as cut-sets, event probabilities, and calculating the probability of the top level event were deliberately excluded. The plan for developing the fault tree was fairly simple. It was composed of the following steps:

1. The entire IRT team would define the Top Level Event and the first "tier" (level) of intermediate events.
2. "Sub-system" teams and team leaders would be formed to construct the various fault tree sections under each of the first tier intermediate level events.
3. The reliability engineer would work with the sub-system team leaders to assist in the construction of the fault tree sections.
4. The reliability engineer would synthesize all fault tree sections into the complete fault tree.
5. The reliability engineer and the IRT manager would decide when a revision of the IRT fault tree was complete. At that time, a meeting of the entire IRT team would be conducted to review every event and gate in the fault tree.

The top level event of the fault tree was defined as *Non-repeatability of the icing cloud.* In addition, the *Non-repeatability of the icing cloud* was defined in terms of measurements, namely, as a non-repeatability in the *test grid measurements* that are taken to characterize the icing cloud. Analysis proceeded by a review of the overall IRT design at a top level with emphasis on identifying functions which were critical to tunnel operation. Functions which could vary, oscillate in output, degrade, or fail, were considered in relation to creating a condition contributing to icing cloud non-repeatability. Once the "key" intermediate events were established (as shown in Fig.2) four teams went into action to develop the fault tree sections connecting to each of the four events.

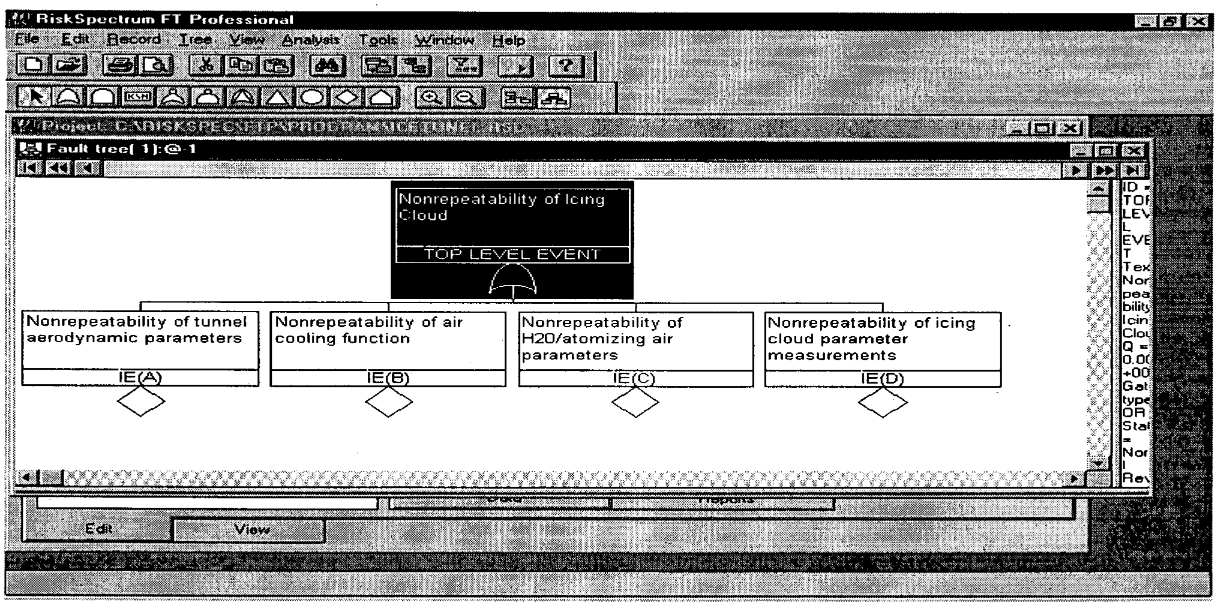

Figure 2 – Non-repeatability of Icing Cloud: Top Level and Intermediate Events.

5. CONSTRUCTING THE FAULT TREE

There were two important challenges that the team had to overcome for the fault tree construction. In brief, these were:

1. To refrain from *immediately* proceeding to one's favorite basic events (faults/failures) as a result of familiarity with the IRT design, operations, and problem history.

2. To determine the first tier of intermediate events (below the top level event) by considering the physical processes, functions, and output required for repeatability of the icing cloud.

The reliability engineer worked with the team leaders by way of one-on-one work sessions where assistance was given to correct mistakes and improve the fidelity of the analysis. The important questions that were always asked were:

1. Are there any events in the fault tree that should be added since the last revision?
2. If we are adding an event to the fault tree ... then Why?
3. Has each event been accurately stated according to what we understand it to be?
4. Have we used the correct logic gates?
5. Should we eliminate a previously postulated fault/failure event from the fault tree without review by the entire fault tree team?
6. Could the operating environment contribute to the intermediate events?

A detailed example of one particular section of total fault tree is shown below:

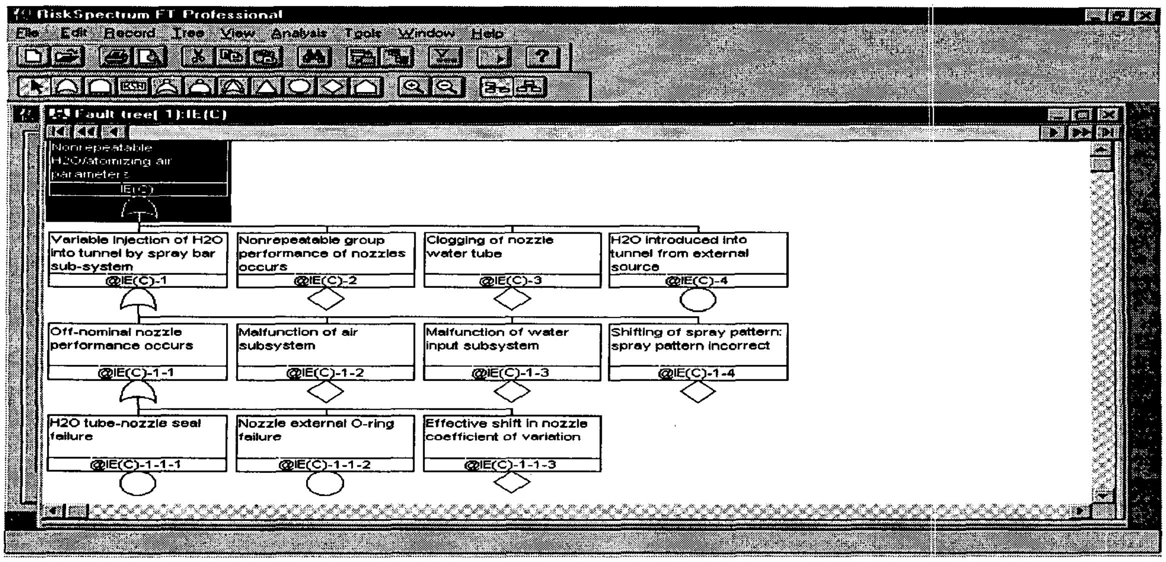

Figure 3 – Fault Tree Section IE©: Nonrepeatable $H_2$0/atomizing air parameters

6. INVESTIGATIONS

Although some damage to the water/air spray bar sub-system (which is used to produce the proper sized droplets in the icing cloud) had to be corrected, it appeared that anomalies in the refrigeration sub-system performance and tunnel aero-dynamics were the relevant variables that could be affecting the non-repeatability of the icing cloud. Many of the postulated events in the complete fault tree were investigated which included the variation of refrigerant flow pressure to the heat exchanger manifolds. The IRT staff observed a peculiar pattern of frost build-up on heat exchanger panels. At times the frost occurred in a "stripe" or "line-like" pattern, and at other times, the frost formed a pattern in a shape that was referred to as "stars." It was conjectured that the non-uniform icing condition was affecting the tunnel aerodynamics. It was believed that the non-uniform icing on the heat exchanger coils created a variation in air flow resistance. This, in turn, created a variation in the air flow patterns into and around the location (general area) of the spray-bar assembly. Thus, the icing cloud created by the spray-bar assembly became non-uniform and specifically, it became non-uniform in a non-repeatable way. The fault tree section under "Non-repeatability of tunnel aerodynamic parameters" (Fig. 2, event IE(A)), contained an event path that could be traced to "non-repeatability effects induced by geometric anomalies," which in turn could be traced to a particular event: "non-uniform icing on the heat exchanger coils." The effort to understand the cause of this phenomenon lead the IRT staff to the possibility that there was a clogging of heat exchanger orifices caused by H_2O contamination of the refrigerant supply. Samples of refrigerant were analyzed, and it was found that the number of parts per million of water in the refrigerant exceeded its upper limit. As a corrective action, refrigeration sub-system filters called "the dryer blocks" which are present to filter H_2O and particulate contamination out of the refrigerant were replaced and were subsequently replaced several more times until much of the contamination was removed. Further investigation lead the team to consider the possibility that the outlet pressure of pumps in the refrigeration system also varied because of low refrigerant. (This affects the net suction pressure of the pumps: not enough refrigerant "starves" the pumps and prevents them from functioning properly. Cavitation becomes a possibility). This possibility was also indicated by the fault tree analysis when the air cooling function (the refrigeration sub-system) was analyzed. The refrigerant level was restored. It is believed that another condition affecting the air flow field, and thus cloud uniformity could have been the heat exchanger vanes. (Theoretically, the air flow-field can be pictured as the trajectory of a particle through the tunnel test-section.) The air flow-field could have been affected by the angle of the heat exchanger vanes. It was learned that some of the heat exchanger vanes had been inadvertently bent in some areas during a maintenance operation. Missing or damaged vanes was a condition covered in the fault tree analysis of the possible "non-repeatability in tunnel aerodynamic parameters." Another corrective action was to straighten the heat exchanger vanes back to their original position.

The shift in icing cloud uniformity during cold temperature operation (at approximately 0°F.), was another observation. Eight thermo-couples were installed on the heat exchanger panels to monitor temperature variations.

Other possible sources of variation in tunnel performance were also considered. An important change from normal operations was that the IRT had to switch over to an alternate source of air supplied for nozzles and was not receiving its usually provided service air from Glenn Research Center which was a dry, clean, service air which normally had a dew-point held at a low and consistent level. This may have had an effect on icing cloud uniformity. The normally provided Service Air was restored and a dew-point meter has now been installed.

During the installation of new nozzles in the water/air spray bar system about 5% of the internal O-rings were cracked or damaged. A contributing factor to this particular problem was the mechanical tolerances for fitting in the new nozzles were small. The "O-ring debris" was transported through the system and lodged in water tubes and in other locations within the nozzle spray assemblies. As a result of this specific finding, all defective or damaged O-rings were replaced and the water/air spray-bar system was completely flushed out. It was understood that although this problem had to be corrected, it could not have been the source of the non-repeatable icing cloud uniformity since the variation in spray output it represented could not explain the day-to-day variations in icing cloud uniformity.

7.FINDINGS AND RECOMMENDATIONS

The Fault Tree was constructed with the intent of capturing every possible idea of the analysis team that might relate to causing icing cloud non-repeatability. Reviews were held by team members to consider the credibility, history, and implications of postulated faults. As a result of these reviews, recommendations for the operation of the IRT were developed. These recommendations, which were made and accepted by the management, are stated below.

A number of concerns by the fault tree team had already been addressed by the IRT staff as part of its operational procedures.

1. The water/air spray bar system is completely flushed out whenever preventative maintenance, corrective maintenance, or upgrades are performed on the system. The flushing operation is also performed whenever IRT team changes nozzle locations on the spray bar assembly.
2. When installing new nozzles or changing nozzles, the staff carefully inspects the installation and checks for the occurrence of tight fit, damage, or leaks.
3. Inspections of the IRT are performed specifically to determine areas of trapped water or tunnel leaks which may permit entrance of water into the tunnel from the outside environment. This is an important inspection since humidity can affect icing cloud uniformity.
4. The IRT practice of periodic calibration check on dial calipers using a gage block standard is performed.
5. An effective software "lockout" is implemented on the spray bar plotting algorithms, computation codes, and graphical display program so that codes cannot be inadvertently changed.
6. At the time of this fault tree analysis, the heat exchanger coils were approximately 50 years old and there was a certain amount of leaking. A major reconstruction of the tunnel and heat exchanger was carried out.
7. The IRT team should provide a program for the WDPF which alarms the tunnel operators in the event that the total water injection for the IRT has exceeded its upper limit. At this point, a decision would have to be made to shut down tunnel operations and defrost before continuing. Following successful calibration of the IRT, and having established the parameter data for an icing cloud uniformity, in the event that the total water injection limit of the IRT is exceeded during a test, a walk-down inspection of the IRT should be conducted and all observations recorded. This recommendation is being considered and its approval depends upon the evaluation of a recent heat exchanger upgrade.
8. Quarterly sampling of refrigerant for H_2O contamination should be implemented. The IRT team can establish a baseline for normal operation and also perform trending.
9. Performance data, specifically the temperature distribution along the length of the spray bar assembly should be investigated. This should include determining the feasibility of adding instrumentation to take these temperature measurements. (This particular recommendation was accepted and has been implemented.)

8.CLOSING REMARKS

The results of this study is shared in order to demonstrate the power of Fault tree analysis as a trouble shooting tool for complex systems or facilities. It is particularly noteworthy that even in the absence of calculating cut-sets and the probability of occurrence for the top level event, Fault Trees are a powerful tool that can be used to focus group efforts for the solution of difficult maintenance problems.

ADKNOWLEDGEMENT

I AM PLEASED TO THANK THE FOLLOWING MEMBERS OF THE fault Tree Analysis Team who worked on the Icing Research Tunnel Project: Harold E. Addy, Charles R. Andracchio, David N. Anderson, Todd A. Austinson, Thomas H. Bond, Timothy J. Bencic, Byron A. Burkholder, Donald R. Canfield, Roger Chamberlin, Douglas C. Dolch, Robert J. Freedman, Jose C. Gonsalez, Robert F. Ide, Thomas B. Irvine, James F. Liebel, Robert J. Manly, Ronald J. Molosky, Gary J. Nosky, John R. Oldenburg, Raymond A. Parker, Andrew T. Post, Jeffrey J. Rusick, David W. Sheldon, William P. Sexton, and John A. Webb.

REFERENCES

[1] See website: http//www.lerc.nasa.gov/WWW/AFED/facilities/irt.html
[2] B. Gulick, A. Young, C. Zalenko, and M. Pollyea, "Icing Research Tunnel History," NASA Lewis Research Center Publication, 1994 Sept, pp. 1-9.
[3] R. H. Soeder, D. W. Sheldon, C. R. Andracchio, R. F. Ide, D. A. Spera, N.M. Lalli, "NASA Lewis Icing Research Tunnel User Manual," NASA Technical Memorandum 107159, 1996 Jun, pp 1-20.
[4] E. J. Zampino, "Icing Research Tunnel Facility fault Tree Analysis (FTA)", NASA Lewis Research Center Internal Technical Report, 1998 May, pp 1-20.
[5] W. E. Vesely, F.F. Goldberg, "Fault Tree Handbook, NUREG-0492," U.S. Nuclear Regulatory Commission, 1981, Jun, Ch. IV, pp. IV-1 to IV-11.
[6] P. L. Clemens, "Risk Management and Fault Tree Analysis II" (a NASA Safety Training Course Notebook by Sverdrup Corp.), 1993 May.
[7] M. H. Packard, V. R. Lalli, "Design for Reliability," A NASA Safety Training Course Notebook by Raytheon Engineering and Construction EBASCO Division and NASA Glenn Research Center, 1994 Jun, Section 10.

BIOGRAPHY

Edward J. Zampino
NASA Glenn Research Center at Lewis Field
MS 50-4
21000 Brookpark Road
Cleveland, Ohio 44135 USA
e-mail: Edward.Zampino@grc.nasa.gov

Ed Zampino earned his MS degree in Physics from Cleveland State University. He worked as a Quality Assurance Engineer for the Technicare Division of Johnson & Johnson in the medical diagnostic instrumentation field. As a Technicare employee, Ed became interested in Reliability when he had the opportunity to work with EIMAC Division of Varian, one of the world's largest producers of X-ray tubes. In 1987, he had the privilege to join NASA and has worked in Reliability supporting many space flight projects. Ed has never left physics alone. He supported the NASA Propulsion Physics Breakthrough Project, and his paper concerning Special Relativity and Electromagnetism can be found in the May 1986 issue of The Journal of Mathematical Physics.