# Control Room Lessons Learned
## A Perspective From F-35A Testing

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# CONTROL ROOM LESSONS LEARNED – A PERSPECTIVE FROM F-35A TESTING

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**Key words:** F-35A, Joint Strike Fighter, Control Room, Flight Test Engineer, Lessons Learned

**Abstract**

The U.S. Department of Defense's largest acquisition program in history, the F-35 Joint Strike Fighter, is a multinational defense program with nine partner nations. As of January 2018, the program's 260+ flying aircraft have flown over 115,000 flight hours at 14 military installations around the globe. The aircraft's flight envelope is proven, munitions are cleared for carriage and the aircraft has reached operational capability. One decade prior, AA-1 was the sole flying F-35 struggling to achieve test points because of immature hardware and software. AA-1 and subsequent developmental test aircraft flights were managed by a control room, staffed by a team of flight test engineers. The evolution from requiring 40 control room engineers for a flight to today's state provides countless lessons learned. This paper encapsulates the flight test period of the F-35A from 2009-2012 and provides practical control room lessons learned from the mistakes and successes made during developmental testing. It is shown that the flight test engineers made advances in control room procedures to accommodate the complexities of the F-35A systems and were thus able to meet the demands of the test program schedule.

## 1. INTRODUCTION

The F-35 Joint Strike Fighter (JSF) weapon system represents a behemoth, both in airplane and in acquisition program. The A-model jet's maximum takeoff weight is 70,000 lb and boasts a wingspan of 35 ft. The single F135 afterburning turbofan produces 28,000 lbf dry, ratcheting up to 43,000 lbf in full afterburner [1]. The multirole fighter is fast at Mach 1.6 and lethal with internal and external weapons carriage capability. But what places the jet squarely in the revolutionary fifth generation fighter category is its avionics, wielding a distributed aperture system and an electro-optical targeting system. The F-35 acquisition program launched in 1992 with first flight of the x-plane variants (X-35, X-32) in 2000 and first flight of the United States Air Force (USAF) variant, the F-35A in 2006 (AA-1) [2]. Costing between 94 and 122 million USD per copy, the United States plans to purchase 2,663 aircraft spanning three military services. Lifecycle cost estimates for the program reach over 400 billion USD for acquisition and over 1 trillion USD for operations and maintenance.

Buried in the lifecycle of a complex, costly weapon system is also a complex and costly flight test and evaluation phase known as System Development and Demonstration (SDD) [3]. The F-35's SDD included the complementary elements: developmental testing (DT) and operational testing (OT) [4]. This paper focuses on DT efforts during 2009-2012 fully acknowledging that the follow-on OT efforts were just as valuable to the program. Though DT and OT are conducted in unison, DT testing must first clear an operational envelope for use during OT. The SDD phase of the program completed in April 2018 after completing over 9,200 flights and 65,000 test points, completely mishap-free [2].

The F-35A's SDD phase began with test article AA-1 in 2006, which flew until its last flight on a ferry mission to Naval Air Weapons Station China Lake for live fire (destructive survival) testing. Within months, the first A-model, AF-1, was ready for flight testing. It was delivered to one of the three flight test locations for JSF flight test, Edwards Air Force Base in California. The other two primary test locations were Lockheed Martin's final assembly facility in Texas and the Naval Air Station Patuxent River in Maryland. The flight test engineering policies and control room operations across the three test sites were managed by the same doctrine, yet this paper specifically addresses the control room lessons learned and best practices at the Edwards location.

The purpose of this paper is to present the techniques used and those innovated by the 100+ discipline and flight test engineers (FTE) at the F-35 Integrated Test Force (ITF) at Edwards. In a fast-paced flight test environment, there is little time to reflect on successes and failures which makes this work even more valuable for future ground and flight test teams. This work is divided into four subsequent sections. Testing Obstacles describes the challenges the test team encountered during developmental testing of the F-35A in its first three years, 2009-2012. Best Practices highlights the very best innovations and tools used by the test team to maintain test safety while achieving the desired test points. Then, the Lessons Learned section reviews the most important takeaways from early F-35A testing. The lessons learned are intended as both inspiration and warning for future flight test teams. Only the three most important lessons were selected for discussion. Lastly, the Conclusions section finishes the paper with a synopsis of the work, then highlights areas for much needed future work on this topic.

## 2. TESTING OBSTACLES

This section describes three testing obstacles that were core to the F-35 developmental testing in the first three years. While there existed many other test obstacles, these three were responsible for spawning many smaller problems. Published Guidance, Configuration Control and Operational Tempo were repeatedly problematic for test execution yielding lost time and cancelled sorties. It became clear in 2009 that these three obstacles were responsible for a disproportionate percentage of the work and rework needed to safely execute test. More attention should have been paid to eliminating these nuisance problems because they continued to percolate for years, unresolved. However, it is hard to focus on systemic problems when the pace of test requires the utmost attention from the entire test team and there is little respite.

### *Published Guidance*

Flight test requires unequivocal guidance provided by a qualified authority, otherwise flight safety can be compromised. There existed a three-way conflict in the F-35 test program between multiple different qualified sources. Because the program was led by the contractor, Lockheed Martin, their published guidance was important. Then the USAF had its own guidance in the form of Air Force Flight Test Center Instructions (now Air Force Test Center Instructions). Lastly, the F-35 ITF had its own operating instructions. It is not uncommon to have multiple sources of documentation but it is a source of frustration for FTEs nonetheless. The authors of each instruction sought to remove any conflicts in the documentation during writing. Further, FTEs were bound by the most conservative (or safest) guidance. Even with these two measures, many grey areas can still exist.

Multiple layers of guidance seek to address different classes of problems for different audiences, yet they are difficult to assimilate and certainly slow processes. One approach to consider is to ensure that any time a conflict is detected within existing guidance, it must be addressed immediately. However, all guidance changes must go through an approval process and new guidance must be promulgated for implementation. This process takes both time and effort, which are are in short supply during an immature DT program.

### *Configuration Control*

Until 2009, AA-1 was the sole flight test F-35. It underwent a series of hardware modifications and software changes as manufacturing and system maturity increased. These gave the team practice at updating their flight checklists, data acquisition software and aircraft knowledge. In 2010, AF-1's arrival at Edwards challenged the test team with a new jet possessing many tangible hardware changes as well as many intangible software changes. To an outsider, the changes between AA-1 and AF-1 were minor but to an FTE, the aircraft's configuration had completely changed. One example is the nose landing gear door on AA-1, which was one panel, opening to one side of the aircraft. AF-1 possessed two nose landing gear doors, opening in the center. The change altered the ground handling characteristics of the aircraft as well as the software. Because of big changes like the nose landing gear doors, those trained for AA-1 operations required additional training (systems, emergency procedures and control room) to crossover to AF-1.

The existential crisis for FTEs came when AF-3 arrived for testing at Edwards. AF-3 was the first missions systems aircraft, meaning it carried more systems equipment that required testing. AF-1 and AF-2 were flight sciences testbeds and matched configuration rather closely, but AF-3 started down a different path having actual avionics and electronic systems instead of ballast and placeholders. For an FTE staffing a morning mission, he might need an AF-1 checklist but would switch to an AF-3 checklist for an afternoon mission. Similarly, control room software loads, aircraft envelope and limits were different. At one point, the Edwards test site had five aircraft with different hardware and software on the ramp for testing with a dizzying array of flight clearances in a variety of stages of approval.

Asking FTEs to switch between configurations daily represented an unnecessary risk. FTEs were arranged into aircraft teams within two divisions inside the Test Operations group, shown in Figure 1. This gave each aircraft team the opportunity to specialize in either Flight Sciences or Mission Systems and limited some configuration control problems. Occassionally staffing shortages necessitated the crossover of Test Conductors and Test Directors but that solution was used sparingly.

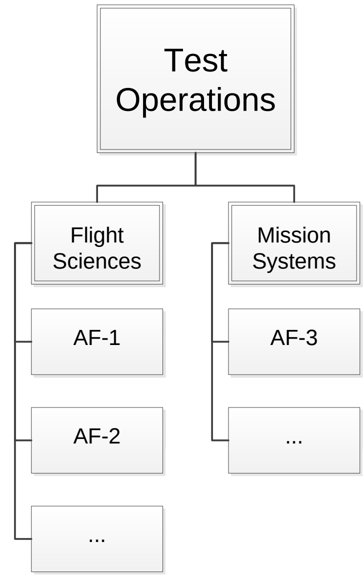


Figure 1: Test Operations Organizational Structure

There are negative consequences to dividing a pool of FTEs into specialized FTE teams. Team unity can be positive but it can also alienate. A Mission Systems FTE could feel it unnecessary to learn the basics of Flight Sciences, which are clearly needed for safe execution of any aircraft mission. Lastly, unusual occurrences and aircraft anomalies occurring for one aircraft are less likely to be learned by all aircraft teams within a hierarchical organizational structure.

Configuration control led to a series of consequences. Those included missed range slots, wrong software configuration in control rooms, lost data and even having the wrong documentation in the control room for a test. Discussing configuration control became a necessary element in pre-mission briefings. Discussing the flight clearance, aircraft software configuration, control room software configuration (including telemetry and data analysis screens) and recent maintenance work on the aircraft helped reduce the human error.

*Operational Tempo*

Everyone in flight test knows that flight test is hard. It is not a secret nor is it avoidable. The operational tempo of any test program is high. The F-35 program, with congressional oversight and nine partner nations was particularly fast-paced. Having two chains of command, Lockheed Martin and the USAF, compounded the feeling of having to serve two masters. In 2009, the SDD phase was behind schedule and flight testing plans were accelerated.

When only two A-models were at Edwards, it was easy to manage the workload. Periodic breakages, impoundments and fleet-wide groundings also injected pauses into the test schedule. Those gaps also increased the pressure on the test team to execute more test points during the available sortie time. This pressure helped to refine methods and increase team efficiency. When the third aircraft, then fourth and fifth reached Edwards, the test schedule became extreme. For many FTEs, the crew duty day of the pilot was their only hope to leave the ITF at a reasonable hour. As the F-35A began testing at further afield test ranges like the Point Mugu Sea Range, mission involvement expanded from a few hours to full day. FTEs would mission-plan one day and execute the next day with very little flexible time in-between. The repetition left little time for additional training or to properly document the previous mission. It was not uncommon for FTEs to eat all three daily meals at the ITF – breakfast on their way into the mission pre-flight briefing, lunch in the control room and dinner after mission debrief.

Weekend operations commenced to meet important schedule milestones. One very controversial set of weekend testing periods occurred between Thanksgiving and Christmas 2010. With weekend flying and no ability to have a few down days, the test team was running dangerously fast. This obstacle led to a whole series of other problems such as missing training events, poorly written test reports, sloppy test cards and lack of forethought for upcoming testing.

Night flying is an apt example that describes how the ITF's operational tempo impacted testing. Night flying developmental test began in the fall of 2011. The build-up approach involved first ground taxiing during low-light conditions, then flights at dusk and finally flights at night. During taxi testing, the pilot discovered that the taxi light was not bright enough to illuminate the region in front of the aircraft. On the F-35A, the landing and taxi light are the same unit to save weight. A bracket redesign to change the angle of the light failed to rectify the problem, but the human factors engineering team changed the refractor geometry and that solved the brightness problem. The first night flight occurred on 18 January 2012 with an aircraft launch prior to sunset. This takeoff time was chosen so the pilot could land during dusk if the lighting was not sufficient for night landings. The test team was incredibly lucky to be expanding the F-35's envelope into night flying during the shortest days of the year during the winter. If this testing needed to be conducted during the summer months, the test team could not have supported operations during the daytime and in the late evening. The team would have had to prioritize between night flying and other testing on other airframes.

A similar example is that of aerial refueling certification. Prior to certification, F-35A aircraft could "hot pit refuel" as a way to lengthen the test day. This procedure is more common in the United States Navy than it is in the USAF. It is where an aircraft lands from a sortie and refuels while the aircraft is still operating. Then the pilot can take off again and conduct another full sortie. Hot pit refueling increases test efficiency because the team only briefs once and can accomplish two full fuel loads of work. Aerial refueling further increases test efficiency, despite the gargantuan cost of launching a refueling aircraft. Both hot pit refueling and aerial refueling the F-35A were lauded by the ITF because the team could accomplish more in a day. However, the FTEs manning a control room for multi-hour missions felt the operational tempo impact.

## 3. BEST PRACTICES

There is very little literature available for FTEs in the form of training manuals or best practices. The most recent, comprehensive reference for this type of work is published by the Society of Flight Test Engineers. Their handbook contains a plethora of technical information related to a variety of aspects of testing [5]. However, a scant four pages of the 401 pages in the 2013 printing relates to control room operations and their handbook is intended solely for members, residing behind a pay wall.

NASA's Aerospace Engineering Handbook contains a basic chapter on flight test engineering and the USAF's dated flight test engineering handbook only reviews the technical aspects of testing [6, 7]. The Advisory Group for Aerospace Research and Development published a report on flight test engineering which contains three vital chapters, building a test team, post flight operations and post test operations [8]. Building the test team is described in detail, focused on qualifications and taskings. The post flight operations chapter discusses debriefs, reports and planning for the next test while the post test operations chapter discusses the activities conducted after the completion of testing. The books by Ivergard and Hunt and Stanton et al both conduct a thorough treatment of control rooms from an ergonomics through design perspective, highlighting the various uses of control rooms and the facets of their design that lead to efficient use [9, 10].

Some universities teach flight test engineering but it remains a niche field with any significant literature contributions limited in audience and exposure [11-14]. Previous work by the author describes the operational methodology in a flight test control room, drawing a comparison to John Boyd's OODA (Observe, Orient, Decide, Act) Loop but that work does not holistically address best practices [15]. The remainder of this section will describe the best practices developed or improved by the F-35 ITF during SDD from 2009-2012.

The core contribution was an online FTE management framework called Control Room Ops Online (CROO). This system was built for the F-22 Raptor developmental test program by a team of software developers and was then brought to the F-35 ITF and improved. CROO enabled FTEs and managers to build reports, view qualifications, build control room teams and even monitor training records. CROO was a solution to the configuration control issues experienced by the program. Figure 2 shows a training screen from CROO, where a manager can select a test location homesite, an FTE and then view qualifications.


Figure 2: Control Room Ops Online User Interface

CROO served as a repository for training records, shown in Figure 3. This consolidated both training forms as well as mission accomplishment reports for easy viewing. Managers could very easily assess an FTE's history with one screen.

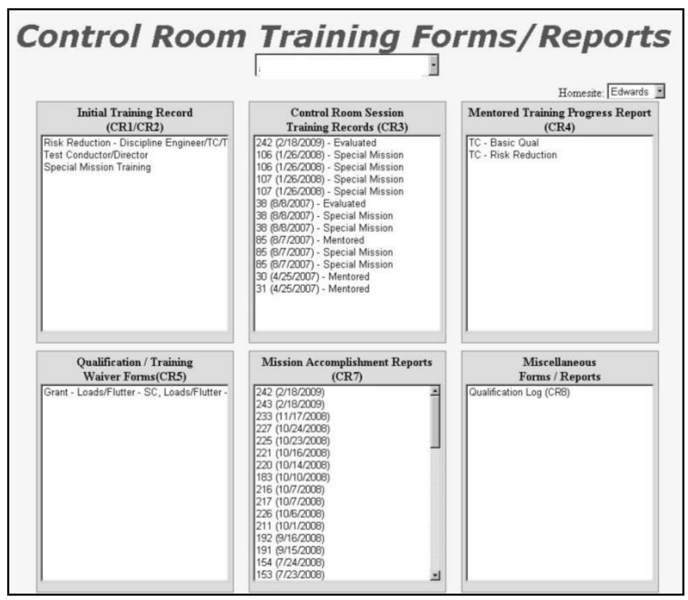


Figure 3: CROO Training Forms Repository

Two other principal features of CROO were the Letter of X's and the Rainbow Report. Shown in Figure 4, the Letter of X's lists the available engineers (FTEs and discipline engineers). Each person's qualifications are then shown. In this figure, "DE" refers to discipline engineer, "T" means that the person is in training and "G," "Y," and "R" represent green, yellow and red. Green is current, yellow is expiring and red means the qualification has expired. This particular screen capture indicates that the control room staff is mainly in the training pipeline. It would be hard to assemble a qualified control room staff.

F-35 Control Room Letter of X's (Edwards)

Control Room | Special Mission

| Name | Organization | Qualifications | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DE - Full Qual | DE - Risk Reduction | Evaluator - F-35 Testing | Evaluator - Risk Reduction | Scribe - Full Qual | Scribe - Risk Reduction | TC - Basic Qual | TC - Full Qual | TC - Risk Reduction | TD - Basic Qual | TD - Full Qual | TD - Risk Reduction |
| | 412 TEG | Y | G | | | | | | | | | | |
| | 412 TEG | | | | | | | | | | T | T | G |
| | Qinetiq | T | T | | | | | | | | | | |
| | 412 TW/ENFM | | | | | | | | | | T | T | T |
| | Netherlands | T | T | | | | | | | | | | |
| | 412 TW/EN | T | T | | | | | | | | | | |
| | Netherlands | T | T | | | | | | | | | | |
| | 412 TW/EN | Y | G | | | | | | | | | | |
| | 412 TW/EN | T | T | | | | | | | | | | |
| | 412 TW/EN | T | T | | | | | | | | | | |
| | 412 TW/EN | Y | G | | | | | | | | | | |
| | 461 FLTS | | | | | R | R | R | T | R | | | |

Figure 4: CROO Letter of X's

Figure 5 shows a sample Rainbow Report. This particular screen capture shows the need for training. Coded by color, a Rainbow Report is a visually useful tool that can help a training manager quickly determine when training should be scheduled. When the colored bands line up conveniently, fewer training classes can be held to qualify the greatest number of engineers.

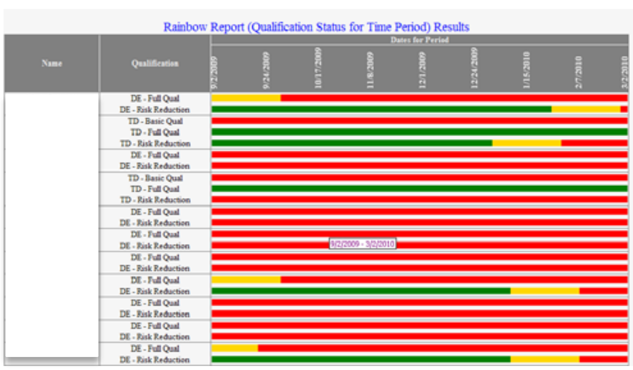

Figure 5: CROO Rainbow Report

CROO was an incredibly valuable tool used by the FTEs in the F-35 ITF daily. It prevented gaps in training, missing qualifications in the control room and even made staffing control rooms easier. The second best practice, however, was just as important to the test program. Emergency procedures simulations (EP Sims) were not invented by the ITF but they were a vital element in the FTE training plan. In their most complex form, these simulations involved a pilot in a simulator with a link to a control room elsewhere on the military installation. This link mimicked the telemetry connection with an airborne aircraft. Control room engineers conducted an ordinary mission using real test cards for practice. Data from the aircraft, airspace maps, actual day-of weather and even a simulated Air Traffic Control element were used to increase realism. The training manager would then secretly inject a single or series of cascading Integrated Caution and Warning System (ICAWS) messages. The manager would then evaluate the control room team and pilot on their handling of the emergency.

EP Sims conducted in the ITF in 2009-2012 could also be less complex. Some simulations were conducted in conference rooms with or without an F-35A pilot. These EP Sims cost less resources to conduct and could be scheduled faster than full control room and simulator simulations. Even less complex EP Sims involved just a pilot and FTE or FTE and training manager in the form of 'chair flying,' where the team mimics flight procedures and communications while seated in a room.

The full range of EP Sim options gave the training manager a set of training tools to use when needed. With each, preparation and scenario development were necessary to prevent negative training. The JSF ICAWS messages are inextricably linked – setting one ICAWS message indubitably trips several others. It was important to understand from a training perspective what failure scenario you wanted to present and then reenact that scenario faithfully. This prevented bogus scenarios that confused more than taught.

## 4. LESSONS LEARNED

Mistakes in flight test can be as benign as failing a test point or as deadly as a fatal accident where both the aviator(s) and the test vehicle are lost. That is why every step of the flight test chain of events is both serious and demanding. During postflight debriefings, the entire mission is reviewed, paying particular attention to the mistakes that were made. In this no-attribution environment, mistakes are used as teaching tools. Highlighting mistakes ensures they become memorable and are less likely to be repeated.

Lessons learned represent a cataloging and summarization of mistakes made during planning and testing activities which is why this paper and in particular, this section, is so important.

In three years of initial developmental testing for the F-35A, the test team made innumerable mistakes. Luckily none cost the team more than minor aircraft damage or a multi-week stand-down. The most frequent mistakes made by the flight test engineers during control room support of testing included being unprepared for a mission, being late to briefings and losing focus in the control room. For sure, technical errors were made in briefings, on test cards and in aircraft data interpretation. Aircraft scheduling errors, test point planning inefficiencies and missed tanker/range times were also frequent mistakes. When a test team is composed of technically gifted professionals, small mistakes are not even noticed because of the layers of backup on the test team. For example, a discipline engineer would need to make a mistake that his lead discipline engineer does not catch. Then that error would need to propogate to the Test Conductor, not be caught by the Test Director then be implemented (and not caught) by the Test Pilot. Having layers in a control room increases safety but comes at the cost of transmission delay.

Among the many lessons learned by the test team at the ITF, the three presented herein were the most often discussed. Solving these resolved many other lesser problems. In summary, the three items are people, training and planning.

*If you don't keep your FTEs happy, they will leave.*

The enemy of progress is the learning curve. Training replacements to replenish positions vacated by highly qualified people is a drain on the remaining team members and takes focus away from the mission. In the F-35 ITF, flight test engineer turnover was staggering. In 2011 alone, one aircraft test team lost more than 80% of its engineers. Some accepted this turnover rate, citing that the test program was aggressive and demanded high commitment and regular overtime from the employees. Others refused to accept high turnover as a reality of the work, citing that it should be a joy to work on such a landmark project, doing things never before accomplished.

Whether viewed pessimistically or optimistically, it remains that retaining your high-quality FTEs is advised. Keeping FTEs happy may take little more than periodic recognition of exceptional performance or reduced work hours. It may also require more nuanced approaches that could include feelings of community or greater feelings of control over a project. Because each individual possesses different motivations, keeping your FTEs happy is not an easy task. Research has found that age is more important to motivations than generational divides (Baby Boomers, Gen X, Gen Y) [16, 17]. On the F-35 program, some aircraft teams started with similarly aged veteran FTEs. As those employees left the program, young, new hires replaced them, exacerbating age gaps and misunderstandings.

Solving the problem of talent leaving is a management dilemma. Management must understand why employees are unhappy then solve the root causes. This can be as easy as talking to employees face-to-face or conducting surveys. There are tangible costs to losing employees so it is worthwhile to invest in keeping them. The lesson for the F-35 team was that it became harder and harder to staff missions with the remaining FTEs after good FTEs left. That increased the strain on the remaining team and in some cases caused more FTEs to leave. Management could have taken a holistic view of how FTEs were treated as a way to prevent future FTE departures.

*If you don't build a robust FTE training program, you will be unprepared for testing.*

Learning curves for highly technical jobs such as flight test engineering can be lengthy, particularly when knowledge mastery of a jet aircraft is involved. Even FTEs who have been working on a similar platform require time to learn the aircraft's software, checklists and quirks. On the F-35A test program, this learning curve took most approximately 12 months from new hire to functional test conductor. It was as short as four months and some never gained mastery and were subsequently moved to other jobs requiring less aircraft knowledge. This variable timeline is impacted by two key factors: availability of training and quality of training. If a test organization takes their training pipeline seriously, they will ensure the highest level of instructors are involved in the program and will craft a training schedule that avoids delays between necessary training events. The ITF approach was to chain together each training event into a multi-week period delivering, at the end, an FTE who could then gain experience before being tested for a qualification.

The quality of training in an organization can change with time yet it is inextricably linked to the passion and experience of the chief instructor. The F-35 program luckily had a stalwart training manager, based at the Fort Worth location, who oversaw the program from its infancy through full-on DT. This manager's experience in the cockpit and control room gave him credibility among his peers. The F-35 test program took training very seriously and the outcome was positive. The control room was no place for unprofessional attitudes or unprepared FTEs. The program achieved a high rate of test execution because the control room staff was trained properly and was able to absorb small changes readily.

There is an inherent inefficiency to training FTEs before they require those skills, but there is also a danger in needing trained FTEs and having none. At least with training FTEs early, the reresh training can occur much more quickly than training from the start. The lesson learned by the F-35 team was that training was done properly. The quality of training was at a very high level and the training was available to the FTEs.

*Your control room plans must be flexible enough to handle multiple jets, configurationss & surge testing.*

Very few test programs are large enough to have one dedicated control room. For F-35 testing, the number was closer to ten across the test sites. At the Edwards test site alone, four control rooms could run simultaneous missions. These control rooms were for the express use of the F-35 program. This benefited the program greatly because the only scheduling conflicts that arose were within the program, from other F-35 missions. Sharing facilities with your own team is easy compared with resourcing across multiple test programs. Nevertheless, configuration control in control rooms must also be looked after. The control room staff must not be the last party to know the aircraft's current software load or its telemetry settings. Otherwise, that can cause delays.

With multiple jets operating every day, the F-35 program experienced problems scheduling emergency procedures simulations and training simulations with control rooms linked to F-35 simulators. In those scenarios, priority was given to live aircraft test missions and control room simulator sessions were cancelled, causing a delay for those FTEs requiring training events. The lesson learned about flexible control room plans is that the system should be designed with flexibility as a tenet. Ensure all available control rooms can support all potential test articles. Allow each aircraft simulator to link to each control room. Lastly, ensure that the control room facilities are staffed to the right level to allow for testing that begins early and ends late.

## 5. CONCLUSIONS

This paper reviewed the period of JSF developmental flight test from 2009-2012 from the flight test engineer perspective. In the absence of a body of literature that captures best practices and lessons learned, this paper tangibly presented the most important of both. Two core best practices were discussed; the use of the Control Room Ops Online training and record-keeping tool and the extensive use of emergency procedures simulations for FTE training. The advancements made by the JSF team were highlighted for both best practices.

Among the countless lessons learned in the JSF test program, three were discussed in this paper. These three lessons are by nature hierarchical lessons. Solving them solves many smaller problems. They can be summarized as such: people, training and planning. Keeping your FTEs happy maintains an intact team and increases organizational efficiency. Building a vigorous FTE training program ensures the team is prepared for testing. Lastly, build control room plans that are flexible to ensure that control rooms are not your testing limitation. While these three lessons were learned on the JSF program, they are not unique to an airframe or program. Being mindful of people, training and planning transcends flight test and is a wise approach in many fields, technical and non-technical.

Future work must be conducted in this subject area. The flight test community does a fair job capturing results of flight and ground testing but does an unsatisfactory job recording the control room operations side of flight test. Procedures for training FTEs and best practices within control rooms are never thought of as the outcome of flight test. However, the absence of published works on this topic is a disservice for future flight test engineers and must be rectified. Every test program should strive to publish one paper that encapsulates the intricacies of that test program from the FTE perspective.

## DISCLAIMER

The views expressed in this paper are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the United States Government.

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