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Human Systems Integration (HSI) for Safety-Critical Range Operations at Wallops Flight Facility (WFF)

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October 2019

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Acknowledgments

The NESC assessment team would like to recognize the following Range Safety Officers (RSOs): Ms. Katie Cranor, Mr. Chip Choquette, Mr. David Helfrich, and Ms. Christine Catrib-Garnier; Mr. John Waterfield, Range Chief Engineer; Mr. Andrew Parkinson from the WFF Software Development Team. The team also thanks Mr. Adam Hajost, RSO at Naval Air Station Point Mugu, California; Mr. Rick Sportsman, Mission Flight Control Officer at Vandenberg Air Force Base, California; and Mr. Walter B. "Barry" Daniels, Supervisor of Range Operations at the 45th Range Squadron, Cape Canaveral, Florida, for their support during this assessment.

The team would also like to thank Mr. John O'Hara, Mr. Chuck Loftin, Mr. Walter B. "Barry" Daniels, Dr. Kelly Burke, Mr. Steve Gentz, Mr. Clinton Cragg, Mr. Robert Hodson, and Mr. Robert Beil for valuable discussions and peer review.

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NASA Engineering and Safety Center
Technical Assessment Report

Human Systems Integration (HSI) for Safety-Critical Range Operations at Wallops Flight Facility (WFF)

August 22, 2019

Report Approval and Revision History

NOTE: This document was approved at the August 22, 2019, NRB. This document was submitted to the NESC Director on September 4, 2019, for configuration control.

Approved:	*Original Signature on File (MK)*	9/4/19
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Dr. Cynthia Null, NASA Technical Fellow for Human Factors	8/22/2019

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Technical Assessment Report

1.0 Notification and Authorization

The NASA Engineering and Safety Center (NESC) Human Factors (HF) Technical Discipline Team (TDT) funded a preliminary study in 2017 that was narrowly focused within the Range Data Display System (RDDS) scope of display design requirements based on schedule and resources. Wallops Flight Facility (WFF) personnel involved in the previous study asked for a broader Human Systems Integration (HSI) involvement that would span both the RDDS and Flight Termination System (FTS) projects and assist with identifying HSI best practices, via appropriate standards and guidelines, that if properly implemented should result in a more effective and efficient Range Safety Operations. WFF Range Safety Operations has expressed a need to assess the roles, responsibilities, and functions of the various personnel on console during launches to identify existing and potential efficiencies and incorporate them in the new system design. This assessment addresses that need.

Dr. Cynthia Null, NASA Technical Fellow for HF, was the NESC lead for this assessment. Ms. Bonnie Novak, HSI consultant, was the technical lead.

The key stakeholders for this assessment are:

- Mr. Michael Morgan, Project Manager, WFF Range and Mission Management Office
- Ms. Debra Parks, WFF Systems Software Engineering Branch

2.0 Signature Page

Submitted by:

Team Signature Page on file – 9/11/19

Dr. Cynthia H. Null Date

Significant Contributors:

Mr. Ronald J. Daiker Date

Ms. Rania Ghatas Date

Dr. Jon B. Holbrook Date

Ms. Bonnie B. Novak Date

Ms. Lisa O. Rippy Date

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization
Core Team		
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3.1 Acknowledgments

The NESC assessment team would like to recognize the following Range Safety Officers (RSOs): Ms. Katie Cranor, Mr. Chip Choquette, Mr. David Helfrich, and Ms. Christine Catrib-Garnier; Mr. John Waterfield, Range Chief Engineer; Mr. Andrew Parkinson from the WFF Software Development Team. The team also thanks Mr. Adam Hajost, RSO at Naval Air Station Point Mugu, California; Mr. Rick Sportsman, Mission Flight Control Officer at Vandenberg Air Force Base, California; and Mr. Walter B. "Barry" Daniels, Supervisor of Range Operations at the 45th Range Squadron, Cape Canaveral, Florida, for their support during this assessment.

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4.0 Executive Summary

NASA Wallops Flight Facility (WFF) is undergoing a major upgrade to its Mission Graphics System and Flight Termination System (FTS) within the Range Control Center Range Safety Room under two separate projects. These safety-critical systems facilitate rapid and accurate decision-making on the part of highly trained users to maintain safe launch operations. In addition, the Range Safety Room is undergoing planned upgrades that include placement of graphic displays, command destruct systems, consoles, and associated equipment.

The WFF Range and Mission Management Office requested the NESC to assess system prototypes; room layout; and roles, responsibilities, and functions of the various personnel on console during launches to identify efficiencies and inefficiencies that can be addressed throughout the upgrade projects.

However, due to the absence of available prototypes during the timeframe of this assessment, the NESC team adjusted the scope to provide best practices and guidance documents rather than evaluations of current or prototype systems. This report provides HSI guidance based on best practices that, if implemented properly during the preliminary and critical design review phases of the project life cycle, should lead to more efficient and effective operations in the Range Safety Room. The level of analysis was driven by the design maturity of the available systems; therefore, the analyses performed are appropriate for these life cycle phases.

The Mission Graphics System, which is being upgraded to the Range Data Display System (RDDS), forms the vital human-machine link that ingests high volumes of system data in real time and displays the pertinent data to NASA's Range Safety personnel, enabling them to assess launch vehicle trajectory and performance status. The system displays the real-time state of the launch vehicle and its complex subsystems to support arm/destruct decisions to facilitate safe launch operations. These decisions are highly time-sensitive, and Range Safety personnel must act rapidly (often within seconds) and accurately to prevent serious injury or death and extensive damage to equipment or property.

In 2016, WFF software development personnel approached the NASA Human Factors (HF) Technical Discipline Team (TDT) about the RDDS development after a presentation at a conference. No NASA policy or process then existed to ensure the application of Human Systems Integration (HSI) and HF design principles to such projects. HSI is included in NASA Procedural Requirements (NPR) 7123.1B [ref. 1]. However, as a specialty engineering area, it is often tailored out and considered to be covered by user community involvement in development and test phases. The NESC HF TDT funded a preliminary study (see Appendix A) that was narrowly focused within the RDDS scope of display design requirements, based on schedule and resources, to demonstrate value and relevancy the HF TDT could bring to the RDDS project. The TDT performed a knowledge elicitation task to derive the informational requirements needed to develop data-driven user information software requirements in support of a new RDDS software upgrade. This task addressed the unique system aspects while focusing on the operational context within which highly specialized personnel operate. The results formed the first step in providing HF guidance to software developers throughout the design, development, and fielding of the new RDDS software graphical user interface (GUI).

WFF Range Safety Operations personnel involved in the 2016-2017 study recognized the value and importance of HSI/HF participation in the project, and asked for broader HF involvement that would span the RDDS and FTS projects and assist in potentially producing a more effective and efficient overall system to support Range Safety Operations. This NESC assessment provides best practices and HSI/HF principles that, if implemented, should lead to:

- Improved decision-making by Range Safety personnel.
- More efficient human-machine function allocation.
- Reduced risks to human life, equipment, property, the environment, and mission success.

The NESC convened an assessment team of HSI experts to review and evaluate the Range Safety operations and provide actionable findings and recommendations to the WFF Range and Mission Management Office, addressing the safety-critical human systems design elements needed for the upgrade project. The assessment team reviewed Range Safety procedural documents and operations plans, flight safety plans, countdown checklists, and relevant government standards; interviewed WFF Range Safety Officers (RSOs); and conducted site visits and Range Safety personnel interviews at Naval Air Station Point Mugu and Vandenberg Air Force Base (VAFB) in California and Morrell Operations Center, Cape Canaveral Air Force Station (CCAFS), Florida.

WFF is the only launch vehicle range wholly operated by NASA, unlike other Agency launch facilities (e.g., Kennedy Space Center) that rely on the Department of Defense to manage range safety operations. Range Safety personnel operate in accordance with NPR 8715.5, Range Flight Safety Program [ref. 2], and NASA-STD-8719.25, Range Flight Safety Requirements [ref. 3], with mission-specific launch procedures outlined in standard operating procedures developed and approved in advance of each mission. This assessment focused on evaluating those operations and providing HF best practices for developing the new systems, selecting equipment, and arranging workspaces within the control center, given the current and changing operational tempo.

WFF launches approximately five expendable launch vehicles (ELVs) and sounding rockets per year, missions are expected to increase to nearly 20 launches per year by 2020 and continue to grow over the next decade. This increase may include up to four simultaneous U.S. Navy Supersonic Sea Skimming Target (SSST) Coyote launches. These are planned to launch serially starting in Fall 2019, increasing to two simultaneous launches, then to four simultaneously by 2022, per Navy plans. WFF is preparing for potential increased mission tempo to support these launches, in addition to Rocket Lab Electron, two Antares, two Minotaurs, potential SpaceX, and existing sounding rocket launches.

The preliminary study (see Appendix A) resulted in a set of initial HF design requirements that were presented to the RDDS software development team. Those requirements were evaluated and rolled up into higher-level requirements more appropriate for a Software Requirements Review, held September 11, 2018.

This NESC HSI assessment for Safety-Critical Range Operations at WFF contains HSI best practices, guidance, references, and design suggestions related to color, luminance, input devices, function analysis, and workspace layout, provided via findings, observations, and NESC recommendations (see Section 8.0) for implementation by the WFF Range and Mission Management Office and the Systems Software Engineering Branch. The team's observations and findings can be summarized as:

- The RDDS and Safety Room upgrade projects could benefit from a dedicated HSI professional to assist in design and evaluation of desired upgrades.
- RDDS prototype systems are immature from an HSI perspective for the design phase of the project life cycle.
- WFF launch operational tempo is due to increase, and the current system setup and room layout is not sufficient to meet the Range Safety Team needs.
- Ample opportunity exists for console redesign, input device, and display changes that could lead to less clutter, better situational awareness, and increased workload efficiencies.

5.0 Assessment Plan

The NESC, at the request of the WFF Range and Mission Management Office and the Systems Software Engineering Branch, initiated an assessment with the following objectives:

1) Evaluate the roles, responsibilities, and functions of the various personnel on console during launches to determine where efficiencies can be identified.
2) Review workspace layout, critical roles, procedures, and operator workload to determine safe and effective function allocations between automation and human operators.
3) Provide best practice design guidance for environmental and display luminance, use of display colors, and input devices for the RDDS.

The NESC assessment team comprised three HF discipline experts from Langley Research Center (LaRC); a human performance subject matter expert (SME) from LaRC and a consultant with expertise in HSI who reviewed WFF mission documentation and range safety plans, identified HF design gaps in existing systems and equipment, determined HSI needs for redesign of the RDDS and Range Safety Room, and formulated actionable NESC recommendations for the WFF Range and Mission Management Office and the Systems Software Engineering Branch. Addressing the NESC recommendations will assist the range safety operations in potentially improving decision-making for range safety personnel; reducing cost through more efficient human-machine task allocation; and reducing risk to human life, equipment, property, environment, and mission success.

This assessment was based on review of range safety procedural documents and operations plans, flight safety plans, and safety room systems and displays; interviews with WFF Range Safety personnel, conducted during the preliminary study and this assessment, and with Mission Flight Control Officers (MFCOs) from the U.S. Air Force launch facilities at VAFB and CCAFS and U.S. Navy launch facilities at Point Mugu; observations of simulated range safety training exercises; participation in WFF RSO training; and observations of a WFF sounding rocket launch and ELV launch, including countdown activities, from the Range Safety Room.

The NESC assessment team received approvals for schedule changes from the original plan, due to the lack of availability of new or prototype systems to assess, the fluctuations of design and implementation schedules at WFF, and the government furlough from December 22, 2018, to January 25, 2019. Other than these changes, the assessment proceeded in accordance with the approved plan, which included the following activities:

- **Conduct a kickoff meeting with WFF stakeholders.** A formal kickoff with the NESC assessment team and the WFF Range and Mission Management Office and Systems Software Engineering was conducted June 28, 2018, at WFF. Mr. Michael Morgan, Project Manager, and Ms. Debra Parks, Systems Software Engineering Branch, presented RDDS and Range Safety Room upgrade status.
- **Review relevant design standards.** The NESC assessment team reviewed 81 documents, including RDDS program range safety, NASA operations, and government design standards; Appendix B contains a list of those documents.
- **Evaluate luminance, color, and input devices for the RDDS.** The NESC assessment team observed and reviewed luminance (e.g., environmental and display), display color usage, and input devices at WFF and the benchmarked ranges along with applicable

standards and guidelines. The team formulated observations, findings, and NESC recommendations (see Section 8.0).

- **Assess workspace layout, critical roles, procedures, and operator workload.** The NESC assessment team observed range safety personnel on console during launches; interviewed personnel in various positions; and reviewed range safety operations plans, flight safety plans, and countdown checklists. The team reported several findings and related NESC recommendations to address these areas (see Section 8.0).
- **Formulate NESC recommendations for function allocation, decision support, and data display based on analysis and findings.** The NESC assessment team observed range safety personnel on console during launches; interviewed personnel in various positions; and analyzed range safety operations plans, flight safety plans, and countdown checklists. The team formulated observations, findings, and NESC recommendations (see Section 8.0).

6.0 Background and Scope

6.1 HSI and HFE Defined

The title of this assessment calls out HSI, but the NESC assessment team determined it best to apply principles from both HSI and Human Factors Engineering (HFE), as defined below. An HSI practitioner will have reachback capability to an HFE to assist in the implementation of the best practices called out in this assessment, as HFE is one of the domains within HSI. Therefore, the NESC assessment team refers to HSI throughout the remainder of this document to avoid any confusion between the two. The only exceptions to this will be in referencing the HF TDT preliminary study and the team that conducted this effort.

HSI is defined in NPR 7123.1B [ref. 1] as an interdisciplinary and comprehensive management and technical process that focuses on the integration of human considerations into the system acquisition and development processes to enhance human-system design, reduce life cycle ownership cost, and optimize total system performance. HSI design activities associated with operations, training, HF engineering, safety, maintainability and supportability, habitability, and survivability are considered concurrently and integrated with all other systems engineering design activities. The HSI process is critical due to the complexity of integration needed to facilitate safe and efficient operations.

HFE is defined in the HSI Practitioner’s Guide [ref. 7] as designing hardware and software to optimize human well-being and overall system safety, performance, and operability by designing with an emphasis on human capabilities and limitations as they impact and are impacted by system design across mission environments and conditions (nominal, contingency, and emergency) to support robust integration of all humans interacting with a system throughout its life cycle. HFE solutions are guided by three principles: system demands shall be compatible with human capabilities and limitations; systems shall enable the utilization of human capabilities in non-routine and unpredicted situations; and systems shall tolerate and recover from human errors.

6.2 WFF Range Safety Background

In 1945, NASA's predecessor agency, the National Advisory Committee for Aeronautics, established a launch site on Wallops Island, Virginia, under direction of Langley Research Center. When Congress established NASA in 1958, Langley was absorbed along with the Wallops Island launch site. WFF is managed by NASA Goddard Space Flight Center in Greenbelt, Maryland, and is capable of launching a variety of orbital and sub-orbital vehicles.

The focal point for all research range operations is the Range Control Center (RCC). Data from the range support instrumentation (e.g., closed circuit television, radar, and telemetry data) are acquired, processed, and made available for video display throughout this facility. This data assimilation, in conjunction with communications and command links, facilitates the coordination, control, and safe conduct of WFF missions. The Range Safety Room, the focus of this assessment, is housed within the RCC (see Figure 6.2-1).

Figure 6.2-1. WFF RCC Mission Control Room

The Range Safety Room (at left in Figure 6.2-1) is adjacent to the Mission Control Room (MCR) and is the focal point for ground and flight safety operations. The functions performed there include wind weighting, monitoring of preflight and flight parameters, and FTS control. The room is separated from the MCR by a glass wall with sliding glass doors [ref. 4].

As stated in NPR 8715.5B [ref. 2], the WFF Range Safety Office operates for the purpose of launching, flying, landing, recovering, and testing space and aeronautical vehicles and associated technologies. These activities, referred to as range flight operations, often present hazards that can pose significant risk to life and property. The scope of this NESC assessment was to assist the WFF Range and Mission Management Office in redesigning the RCC Range Safety Room to support continued protection of the public, NASA workforce, and property during range operations associated with flight.

The key technical objectives for the WFF Range Flight Safety Program are to:

- Ensure operations undergo a range safety risk analysis to establish any design or operational constraints needed to control hazards and risks to life and property.
- Contain or mitigate the risk to the public, NASA workforce, and any property requiring protection from debris impact or other hazards associated with vehicle flight.
- Ensure proper risk acceptance decisions are made that integrate concerns for all identified hazards for the range flight operation and ensure Agency risk criteria are satisfied.
- Ensure launch/flight commit criteria for a range flight operation are identified and dispositioned prior to initiation of flight or phase of flight (to include entry, landing, and recovery operations).
- Make real-time operational decisions (e.g., flight termination), when required to control risk. These occur prior to initiation of flight, prior to each phase of flight, and during flight up to orbital insertion and during recovery.

The preliminary study team, assembled through the NESC HF TDT, first met with the WFF Range Safety and RDDS software teams in 2016 to discuss and identify early human-centered requirements for the next version of the RDDS software upgrade. The Range Safety personnel indicated they were planning significant software and hardware upgrades in the development of the new RDDS. They had identified a new FTS panel, and these changes would necessitate new display monitors, potentially new input and pointing devices, and a new work station to hold the physical components. However, the development of the new RDDS, along with the computers, displays, and other devices, was being managed as a separate project from the work station and work space for the range safety officers. The team noted during the preliminary study that, due to the integrated nature of the Mission Graphics System, the consoles, and the FTS panels, an integrated management approach would be most effective. When this NESC assessment began in 2018, one project manager was responsible for the entire upgrade. Therefore, it was imperative that the NESC assessment team re-engage to provide best practices, based upon HSI standards and design guidelines, as well as benchmarking other range safety facilities to understand the overall operator environment for integrated software and hardware.

Originally, the Range Safety Room console was designed for four personnel. A fifth position, the Assistant Flight Safety Officer (AFSO), had been added by 2016. The software and range personnel were interested in whether that number could be reduced to four and how that would affect workload, task distribution, and/or safety of operations. When this assessment began in mid-2018, the NESC assessment team noted the previously-staffed AFSO position had been removed from the Range Safety Room console. During interviews with the NESC assessment team, WFF personnel attributed the change to a management decision due to staffing availability to support necessary remote launch operations. Other than that, no changes had been made to launch staffing or the room layout since the team’s initial visit in 2016.

Range safety personnel make highly critical time-sensitive decisions to prevent serious injury or death and extensive damage to equipment, property, and the environment. Prior decision support systems were designed without systematic application of HSI principles. The NESC assessment team focused its HSI analysis on areas of significant impact in the Range Safety Room, including color and luminance analysis of the RDDS, input devices used on console, and layout of the

Range Safety Room with analysis of staff roles and responsibilities. Figure 6.2-2 shows the Range Safety Room Console.

Figure 6.2-2. Range Safety Room Console

7.0 Assessment Approach

To conduct this assessment, the NESC assessment team needed to understand the scope of mission requirements and roles of personnel on console. The assessment team collected data during documentation review from applicable NASA and federal government standards and technical reports; conducted site visits and MFCO interviews at Point Mugu, VAFB, and CCAFS; performed literature reviews; and observed launches of the RockSat-X and Antares from the WFF Range Safety Room.

The NESC assessment team created Table 7.0-1 to capture similarities and differences in the vehicles launched from each of the benchmarking sites. Operations at CCAFS and VAFB are most closely aligned with those at the WFF Range Safety Room, while Point Mugu, primarily a weapons testing facility, was visited to understand operations of SSST (Coyote) launches as opposed to more comprehensive operations on console.

Table 7.0-1. Vehicle Launches for Four Ranges

Launch Site	Coyote	Minotaur	Sounding Rockets	Antares	SpaceX	Rocket Labs Electron
WFF	2019	√	√	√	TBD	2019
CCAFS		√			√	
VAFB		√			√	
Point Mugu	√		√			

Similarities and differences exist across all four facilities in staffing, operations, missions, training, room layout, and console design. Each facility also has similarities and differences in terminology for the positions on console and their roles. See Table 7.0-2 for a quick overview.

Table 7.0-2. Range Safety Operations Position Comparisons for Four Ranges

Role	WFF Term	CCAFS Term	VAFB Term	Point Mugu Term
Monitors Flight Termination System (FTS)	*Flight Safety Officer (FSO)	*Mission Flight Control Officer (MFCO)-2/Other range members that monitor the FTS are Telemetry Systems Officer (TSO)/Pad Safety (located with the user)/Safety Analyst (located in the same building)	*MFCO	
Overall Safety Console Management	*Range Safety Officer (RSO)	*Range Operations Commander or Senior MFCO (SMFCO)	*Senior MFCO	*Range Control Officer (RCO)
Surveillance	*Surveillance Officer (SO)	Surveillance Control Officer (SCO)/ Surveillance not collocated—separate room with multiple staff	Aerospace Control Officer (ACO)—sea, air, train (not collocated) Launch Support Team (LST) —land (not collocated; in the field)	*RCO
Vehicle Health Monitor	*Systems Safety Officer (SSO)	TSO	*Flight Safety Project Officer (FSPO)	
Command Positions	*ACDS Data Manager or Command (New position will be on console)	*Command Systems Officer (MFCO-in-training or a certified MFCO)	*Command System Controller (CMD)	
Launch Pad Observers	Sky Screens	Forward Observer Ground (FO-G) or Wire (for Wire Sky Screens (WSS))	Forward Observers	N/A
Provides Minus Count Wind Update Data	Wind Weighting	Wind towers and/or balloons released from the Balloon Release Facility	Flight Safety Analyst (FSA)	
Assist MFCOs in Making Real-Time Changes to Displays or Switch Data Sources, if Needed	N/A	*Range Safety Coordinator (RGNext Contractor)	*Real-Time Data Controller (RTDC) - 2	
Telemetry Monitor	*RSO *FSO *SSO	*TSO	*Telemetry Observer (TMO)	

Note: ***** denotes position on console and collocated with Range and Flight Safety Officers during launch operations

7.1 Operations and Personnel

From 2016-2019, WFF has seen growth in launch operations and reduction in Range Safety operators on console. Over the next few years, many changes are expected for WFF launch operations. WFF, with the RDDS development, is reassessing what operator positions are needed to support launch operations and what RDDS automation can provide to support the operators in timely decision-making. As Tables 7.0-1 and 7.0-2 illustrate, the NESC assessment team assessed both types of launches and launch operations personnel on console in Range Safety Rooms or in other locations for three additional launch facilities.

In 2016, WFF was conducting one or two launches per year with an FTS on board. Now WFF is bringing in new customers, missions, and launch vehicles. The number of launches requiring staffing is expected to increase to nearly 20 per year by 2020, continuing to grow over the next decade. Some of these launches will likely be classified. As the number of launches at WFF has grown, the number of Range Safety operators on console has decreased by one. In 2016, there was an AFSO position that has since been removed; that position's responsibilities have been absorbed by the RSO. WFF is considering additional Range Safety operator changes for launch operation, including the elimination of the SO position (either entirely or from the Range Safety Room) and the addition of a Command position.

Several WFF RSOs reported to the NESC assessment team that there is discussion concerning either eliminating the SO position and having that function absorbed by other operators on console or moving the SO to another location, but no final decision has been made. Based on NESC assessment team observations, VAFB has a SCO position, similar to the WFF SO position, as noted in Table 7.0-2. In contrast, the SO and RSO at WFF consult closely concerning the analysis and use of data from the Surveillance Command (SC), which is not located in the Range Safety Room, to determine how to proceed.

With the addition of the new Advanced Command Destruct System (ACDS), a proposed new Command position is envisioned within the Range Safety Room. The scope of this position is being defined by the WFF Range and Mission Management Office, but the Command position is expected to be responsible for monitoring the ACDS system and all vehicle status data. This scope could potentially evoke a sustained high cognitive workload environment and should be assessed to determine operator capabilities and limitations. The ACDS provides the encrypted command destruct links between the vehicle and the ground for one individual arm/destruct function. This system monitors the status of a flight termination system, including all components on board a launch vehicle that receive a flight termination control signal and achieve destruction of the launch vehicle [ref. 5].

The Command and SSO console positions, per WFF RSO, should be positioned next to each other to enable effective collaboration and coordination, since the Command position is essentially an extension of the SSO position. Additionally, the two wind weighting positions are within the Range Safety Room. These positions are staffed only for sounding rocket launches. At Point Mugu, wind weighting personnel are in a separate room and data is relayed via phone.

CCAFS and VAFB have surveillance and risk management personnel in different locations from the Range Safety operators on console. At WFF, risk management personnel are not collocated. Additionally, the NESC assessment team noted that communication protocols seemed to be an issue at all ranges, which could be attributed in part to a concern about the ability to perform sufficient recurring staff training. However, VAFB reported that even with what they consider a robust training program, communications protocol issues occur during off-nominal events.

As noted, further changes are expected in terms of operations and flight termination during WFF launch procedures. For example, commercial space companies like SpaceX use the Automated Flight Termination System (AFTS), also known as an autonomous flight safety system. The Air Force has mandated that its major launch ranges, CCAFS and VAFB, will transition to AFTS in 2022. However, WFF, as a NASA range, and Department of Defense (DoD) ranges (e.g., Eglin AFB) are not required to meet this mandate and will continue to use conventionally commanded systems. WFF will need to position itself to support AFTS and conventionally commanded missions in the future in order to support additional launch customers.

The NESC assessment team assessed the roles, responsibilities, and associated functions of the four current WFF console positions (i.e., RSO, SO, SSO, and FSO) using the Mission Graphics System layout during several types of vehicle launches to determine where efficiencies could be identified. These console positions were observed by the assessment team for two mission scenarios: ELV and Sounding Rocket. The NESC assessment team observed a RockSat-X launch on August 13, 2018, and an ELV Launch of the NG-10 Antares on November 17, 2018.

7.1.1 Range Safety Officer

The critical role of the WFF RSO is to ensure public safety during launch operations. The RSOs and their range safety team enforce the launch safety policy. They are responsible for preventing a launch from occurring if launch safety criteria are violated during the countdown, and for monitoring the vehicle in-flight and sending terminate functions if the vehicle poses a public threat. The *RSO* is synonymous with *SMFCO*, which is used at Navy and Air Force ranges.

Responsibilities of this position prior to launch include conducting command system confidence checks, confirming global positioning system (GPS) weather balloon releases, providing wind weighting settings, reporting toxic analysis statuses, providing status of surveillance assets, communicating with skyscreens (outside observers referred to as “Back-Az” and “Pitch”), monitoring Interface Region Imaging Spectrograph (IRIS) Range Safety (RS)1 and RS2 displays during nominal and off-nominal flight, conducting flight narration of key flight events and verbalizing observations [ref. 29], verifying collision avoidance status with the Test Director (TD), and making the final Range Safety “GO FOR LAUNCH” call to the TD.

These duties occur at predetermined times during countdown and require input from other positions on console. The RSO is also responsible for leading the Range Safety Team, which includes not only the other three positions on console, but also the Operational Safety Officer; Ground Safety Officer; Skyscreens (1 and 2); Risk Assessment Center (RAC); Debris, Toxics, and Distant Focused Overpressure (DFO); and Wind Weighting. Finally, if necessary, the RSO is responsible for communicating on the communications network “Launch Abort Condition,” which requires switching the light tree to red if in terminal count; activating abort; and announcing “Abort, Abort, Abort” condition.

As previously mentioned, the AFSO position on console has been removed. The AFSO was responsible for monitoring the Vehicle Status Display and calling out staging events and vehicle attitude. These duties have been absorbed into the RSO responsibilities. In addition, during sounding rocket launches, the RSO is responsible for tracking high-altitude GPS balloons to maximum altitude and monitoring radar sites performing point-in-space and slaving checks.

7.1.2 Flight Safety Officer

The FSO is responsible for performing FTS checks during countdown, making the "GO FOR LAUNCH" call to the RSO, monitoring IRIS RS3 and RS4 displays during flight, and performing real-time flight termination decision functions during flight based upon rules in the Flight Safety Plan. This is another safety-critical operation, due to the responsibility of monitoring the vehicle in flight in order to make a destruct call to terminate the vehicle, if necessary.

The assessment team observed during simulated Antares launch training that the FSO was responsible for conducting flight narration of key flight events and verbalizing observations, although review of RSO Training Module 1 states that this is an RSO responsibility. The lead RSO during training shared that this is ultimately an FSO duty, and they practice as such.

The FSO monitors the FTSD, radar, and telemetry data via range data processing and display computers, and is responsible for knowing the FTS flight mission rules, which are generally printed out and kept on console as job aids. In discussions with FSOs and MFCOs at other ranges, using these printed job aids is typical and often encouraged, due to the criticality of the information and the fact that mission rules vary by mission.

O-1. WFF training material, *Module 1 Roles and Responsibilities*, does not match the operational practices of the RSO and FSO as observed during simulated training and launches.

7.1.3 System Safety Officer

The SSO works alongside the FSO during countdown FTS checks, determines that all pre-launch FTS checks have been satisfactorily completed, monitors all FTS state of health data, reports anomalies to the FSO and RSO on the ground and during flight, monitors the arming of the FTS, and makes the FTS "GO FOR LAUNCH" call to the RSO. In addition, the SSO is responsible for monitoring and calling out vehicle health over the communications network, controlling nominal command transfer from WFF to the Bermuda Tracking Station, relaying a verbal code word that serves as a secure identifying password to the active command site, and monitoring range safety FTSDs on IRIS RS5.

7.1.4 Surveillance Officer

The SO verifies clearances, Notices to Airmen (NOTAMS) and Notices to Mariners (NOTMARS) with the TD and reports to the RSO, clears any air and sea traffic from within the launch danger zone, alerts the RSO to safety issues regarding traffic entering the zone, reports go/no-go status to the RSO, coordinates and communicates with the RSO, and maintains awareness of the duration of loss-of-signal in relation to destruct requirements.

7.1.5 Operations and Personnel Summary

In addition to the preceding descriptions of the roles and responsibilities of each position on console, operational and HSI considerations will be addressed below. All of the above positions will be addressed further in the function analysis section (see Section 7.6.2). The following sections present analysis and best practices for specific areas requested by the Range Safety Team, including general HSI and existing functions and roles, workload efficiencies, room layout, workstation, input devices used on console, and RDDS color and luminance design considerations.

7.2 General HSI

Several offices are working concurrently on redesign of RDDS graphic displays, ACDS rack position and placement, Range Safety Room layout, and selection and acquisition of new mounted racks and consoles. Given that these activities include humans as a critical component in the system, engaging an HSI practitioner on a part-time basis throughout the course of the project is essential. This HSI practitioner would be responsible for ensuring that human-operator capabilities and limitations are considered throughout the design life cycle, to include design, layout, implementation, and deployment across all system components. Additionally, this HSI practitioner would have the access to reach into the HF community to call on subject matter expertise and support as needed, as well as to facilitate communication among project personnel in the various disciplines.

F-1. The WFF Range Safety Operations Office has no HSI practitioner on staff to help integrate RDDS and Range Safety Room equipment layout for safe and efficient operations.

R-1. Engage an HSI practitioner to work concurrently across project offices and alongside RSOs and members of the Systems Software Development Branch, as needed, to ensure human operations operator capabilities and limitations are effectively addressed throughout the Range Safety Room redesign effort and project life cycle. (F-1)

7.2.1 HSI Best Practices in the Project Life Cycle

The current Mission Graphics System used on console in the WFF Range Safety Room is over 20 years old, and the host hardware is no longer manufactured or vendor-supported. The new RDDS is intended to provide WFF with an improved graphics system to monitor mission status and enhance situational awareness. The RDDS will be configurable to ingest a variety of available tracking data sources and output a variety of graphical and textual displays. It will support pre-launch simulations, real-time launches, and post-mission analysis.

The RDDS system is being defined, and the Software Development Team is in Phase B of the life cycle process. As stated in the NASA Systems Engineering Handbook [ref. 6], the goals of this phase are to "define the project in enough detail to establish an initial baseline capable of meeting mission needs." Standard practice for HSI support during Preliminary Design Review, as outlined in the NASA HSI Practitioner's Guide [ref. 7], includes evaluating design and display submissions and conducting a thorough review of design features from a human performance and usability perspective. Ideally, this would be conducted by the project's assigned HSI practitioner. However, as WFF does not have this skill, the NESC assessment team had the opportunity to provide high-level input and guidance during the timeframe of this work, even though no prototypes were available for evaluation. Based on guidance from NPR 7123.1B [ref. 1], the Systems Engineering Handbook, and the HSI Practitioner's Guide, the HSI requirements provided during the preliminary study should continue to be refined, implemented, and validated to ensure the operational concept is technically sound (including HSI interactions).

F-2. HSI analysis of the RDDS design has not been performed.

R-2. Apply HSI considerations and NASA system requirements guidance throughout the project life cycle. *(F-2)*

7.2.2 HSI Operational Observations

The NESC assessment team observed the NG-10 Antares and RockSat-X launches and numerous training simulations leading to those events. While training materials and range safety plans are available to train personnel on a mission-specific basis, no overarching standard WFF operating procedures exist that contain protocols for standardizing terminology, communications, and best practices for WFF Range Safety Room console positions on console. The assessment team noted, during the WFF launch training and subsequent launches, that the lack of communications standardization led to informal chatter among console operators, lack of clear roles (e.g., RSO versus FSO), and inconsistent use of terminology. Specific examples follow:

- During the RockSat-X launch, with less than T-15 minutes until liftoff, an 80-foot patrol boat was detected in the launch hazard area. The SO performed risk calculations by hand to determine go/no-go for launch. Several people crowded around the SO position on console, looking at the SO's displays, asking questions, and attempting to help make the call. The NESC assessment team observed that this informal crowding could lead to increased stress on the SO. Although the SO did not report increased stress, the situation could have adversely affected his calculation accuracy, decision and/or timeliness in making the go/no-go launch determination. The NESC assessment team believes that with proper training and discipline, the informal crowding scenario could have been avoided.
- The WFF Range Safety Team conducted training in preparation for the Antares launch October 29-31, 2018. The NESC assessment team was invited to observe training simulations and crew operations as part of the data collection effort. During the first day of training, several personnel switched between the RSO and FSO positions for the purposes of cross-training. The assessment team noted that the roles and responsibilities of these positions changed depending upon the person in position on console. For example, during the majority of simulations, the RSO performed the launch countdown, called vehicle health status, performed clock management, and provided confirmation of command checks. However, these responsibilities are primarily FSO assignments. In addition, the assessment team noted several instances when informal communications took place outside the network channel (e.g., "Yeah, I'm tracking; I'll watch it," in reference to the RSO noting abnormal steering of the vehicle. The terms "copy," "roger," and "yeah" were used interchangeably over the network. All of the above are part of the WFF RSO Training that the NESC assessment team observed in August 2018. During interviews, CCAFS MFCOs reported that their monthly training reduces such informal communications. CCAFS uses a scripted communications pattern that improves communication efficiency and reduces communication errors.

During site visit interviews, MFCOs at VAFB and CCAFS described training standardization as a critical component of successful operational effectiveness. CCAFS Senior MFCOs stated that they train monthly for optimal mission performance.

F-3. No overarching WFF standard operating procedure exists.

R-3. Investigate whether operational efficiencies could be obtained by developing an overarching standard operating procedure for WFF Range Safety Operations. *(F-3)*

O-2. During launch simulation training, the WFF RSOs did not follow a standardized communication protocol.

R-4. Develop a comprehensive recurrent training program to improve operational adherence to standardized console processes and communications included in the RSO Training Modules. *(O-2)*

7.3 Range Safety Room Layout

7.3.1 Current Range Safety Rooms Overview

The WFF Range Safety Room has been in the same location and largely the same configuration for many years. This area has two access points: from the MCR, with which it shares a large glass door and wall, and from the RAC. The RAC contains the DFO/Toxic Area, as shown in Figure 7.3-1. Non-essential personnel walk through this room to reach other areas of the building. No physical means restrict access during launch preparation and execution. This layout creates privacy and distraction concerns for WFF Range Safety personnel on console. Also, because of the openness, other launch personnel feel free to enter the Range Safety Room during launch preparation or during nominal and off-nominal launch events. There are exterior windows at one end of the room.

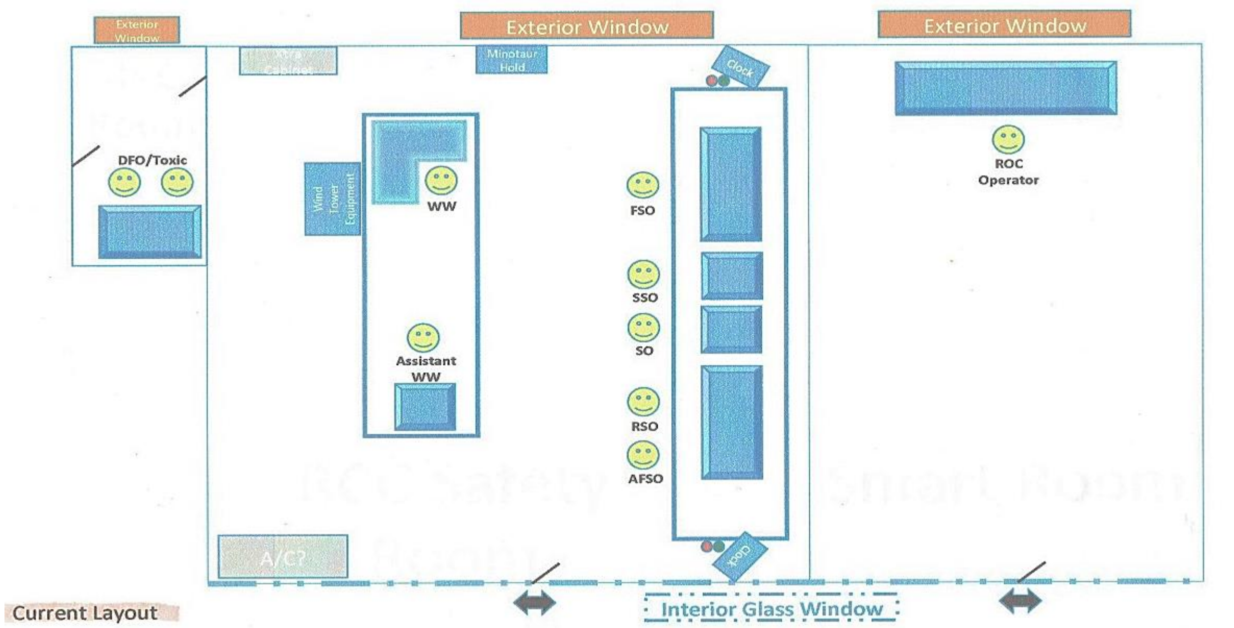

Figure 7.3-1. Range Safety Room Layout

The primary console within the WFF Range Safety Room is laid out in a straight line with the FSO and RSO seated at opposite ends, which is unlike any other facility the NESC assessment team benchmarked. The placement of the RSO and FSO was explained as a previous WFF management decision to ensure that all communications between the two operators were recorded on the network, which is especially important under off-nominal conditions. The rationale was that if the two operators were next to each other, they might inadvertently forget to use the communications network when discussing the operation for decision-making and therefore significant communications would not be recorded. Imposed physical separation is one approach to mitigating a potential unrecorded communications issue, but it does not guarantee that all voice communications will be recorded. During the RockSat launch, the NESC assessment team noted that Range Safety operators were out of their seats and off of the communications network to discuss the pre-launch vehicle identified by the SO. Furthermore, the Range Safety Operators at WFF believe that this physical separation causes other operational inefficiencies. Due to the amount of coordination and collaboration and the need for situational awareness between these two positions when making safety-critical decisions, the WFF Range safety operators would prefer these two to be placed where they can easily see each other's displays and cross-check each other in the redesigned Range Safety Room.

F-4. The FSO and RSO are separated, with two consoles and operators between them.

R-5. Position displays to enable coordinated decision-making and cross-checking between the RSO and FSO. *(F-4)*

The CCAFS Range Safety Room design is shown in Figures 7.3-2 and 7.3-3. A video position is included, which is the third MFCO, usually a SMFCO, who sits between another MFCO and the SMFCO. This position often serves as the range safety lead, monitoring the overall picture during launch operations. When asked what they would change about their workspace design, CCAFS personnel said the overall console needed to allow the three MFCOs to more easily see each other's displays. CCAFS performs approximately 30 launches per year with 5–6 operators on console for conventional command missions, and fewer operators for customers using AFTS.

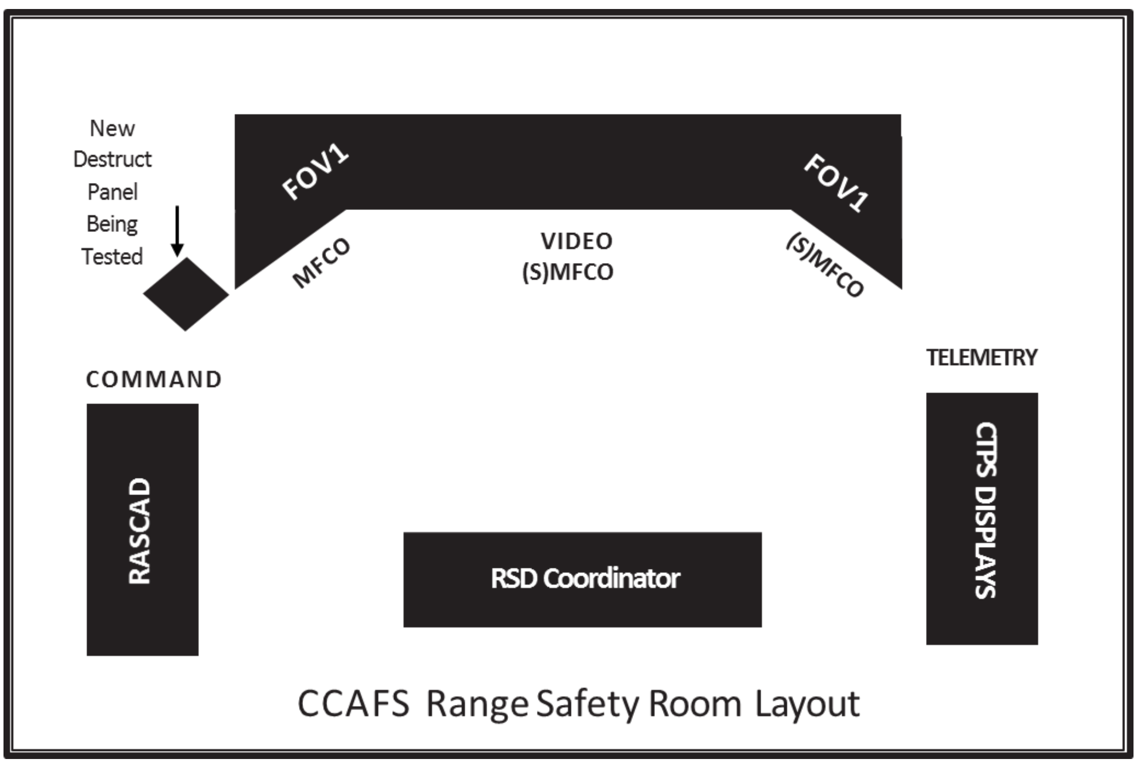

Figure 7.3-2. CCAFS Range Safety Room Layout

Figure 7.3-3. CCAFS Safety Control Room

The VAFB Range Safety Room layout is shown in Figure 7.3-4. VAFB personnel indicated that 20–25 people are usually in the room during a typical launch, with 19 positions identified on console. The room is access controlled and is considered a quiet zone during launch operations. The seats in the middle of the room are for observers; they are stationary, so observers remain at a fixed distance from the operators. Not shown are bookcases behind the MFCO, SMFCO, and CMD console positions. The bookcases hold binders and reference material, personal belongings, and other items brought into the control room that may be used pre-launch, but are not needed after launch. These serve two purposes: keeping the console as clutter-free as possible, and forming a physical barrier between operators and observers.

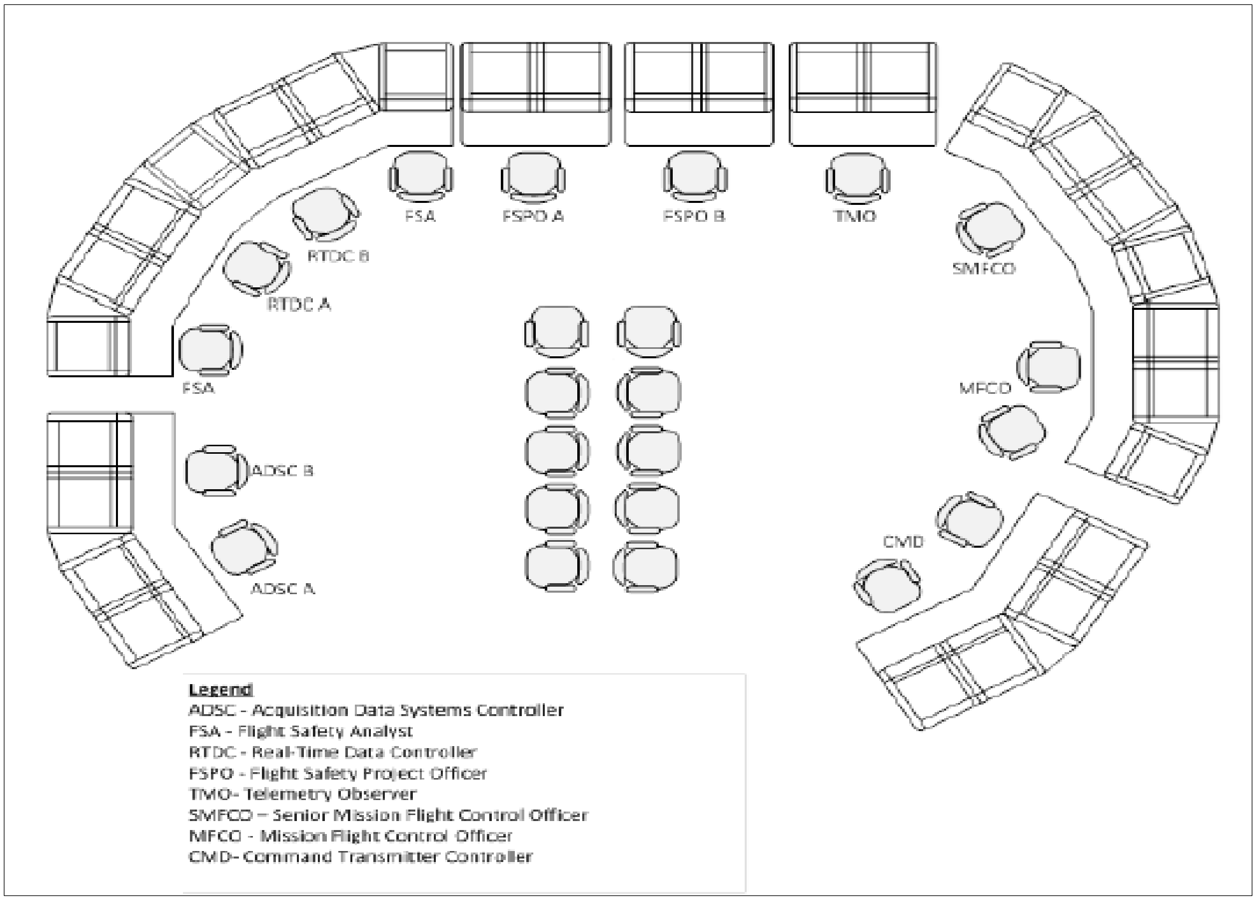

Figure 7.3-4. VAFB Range Safety Room

While the NESC assessment team was unable to obtain pictures or drawings of the Point Mugu Range Safety Room, it was noted that a typical launch has only two positions on console, identified in Table 7.0-2. These operators are sitting in a large open room with the full launch and data team. Additionally, they do not have visual observers or video of the launch pad, but they expect to add these capabilities in the future. Point Mugu performs a couple of dozen launches per month, approximately 1,000 launches per year.

7.3.2 WFF Proposed Range Safety Room Redesigns

Many redesign ideas for the WFF Range Safety Room have been developed. WFF provided the NESC assessment team with materials dating prior to 2012. As previously noted, the Range Safety Room has not significantly changed or been updated since the 1990s. This section will discuss three Range Safety Room redesign proposals brought forward recently by WFF Range Safety personnel (see Figures 7.3-5 through 7.3-8).

Some of the primary issues and objectives discussed during site visits to WFF that were to be included in the redesign of the Range Safety Room included:

- Ability to support classified operations
- Ability to support near-simultaneous operations
- Ability to adequately train operators without negative impact on operations

- Ability to control access to the Range Safety Room to minimize distraction
- Operator comfort (e.g. lighting, food/beverage accessibility, noise)
- Enhanced coordination and collaborative decision-making ability for operators on console
- Ability to limit and/or control visitors/observers within and around the Range Safety Room

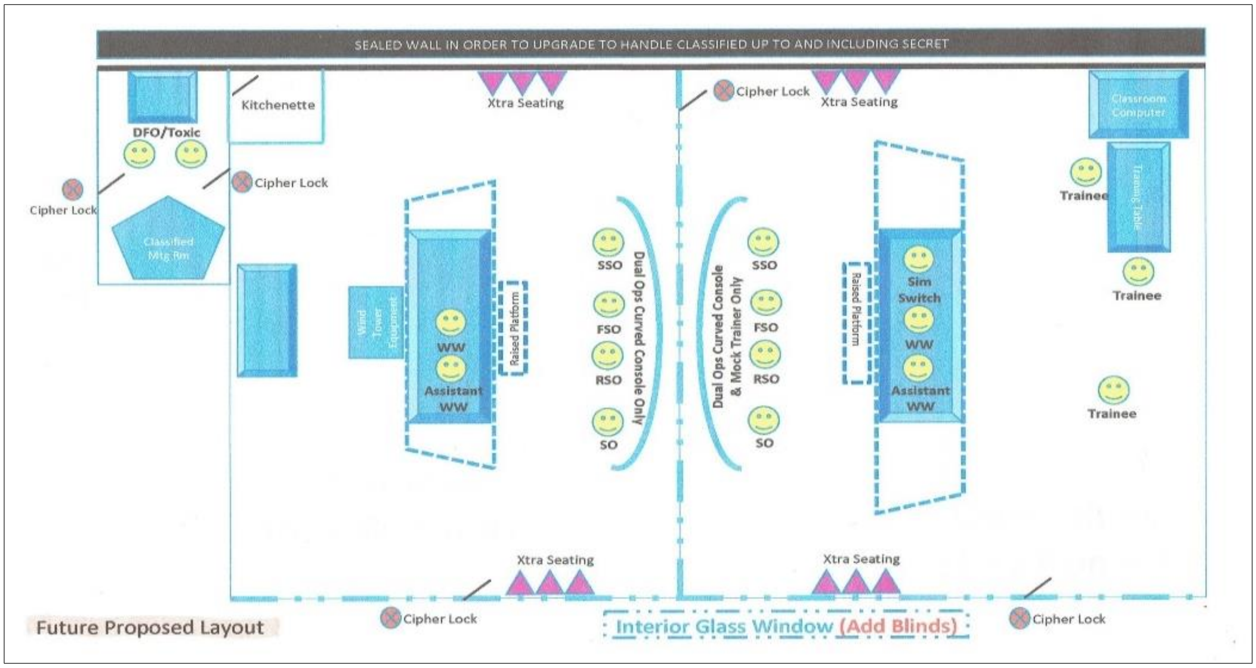

Figure 7.3-5 WFF Range Safety Room, Future Concept #1

Common Assumptions/Requirements

- Remove windows; wall over
- Remove glass between the Range Safety Room and RCC; wall over and install door
- Install viewing platform for visitors
- Theater seating with 3 MOVE panels
- Cipher lock on entry doors
- Consoles adaptable for multi-use, if possible
- Due to drop ceiling, video wall not feasible; RSO/FSO/SSO console will have video monitors to the ceiling
- Top video monitors will be visible from WW#2 and CMD consoles
- Must accept WV command panel racks (already purchased) at RSO and FSO consoles
- Must accept WV command racks at CMD console
- MOVE will be communications panel solution
- Compatible with potential RDDS design and human interface

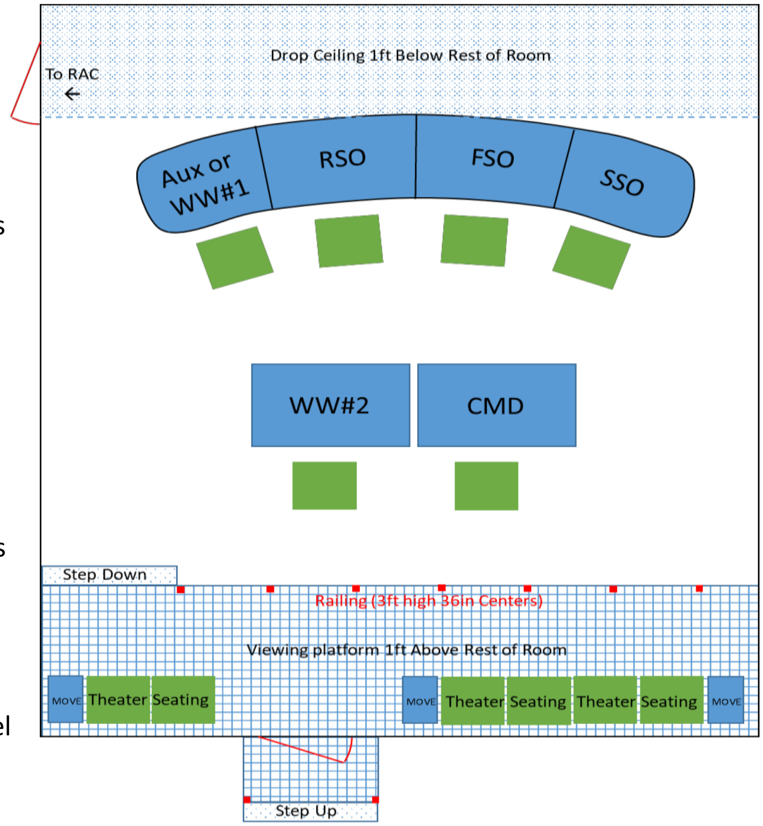

Figure 7.3-6. WFF Range Safety Room, Future Concept #2

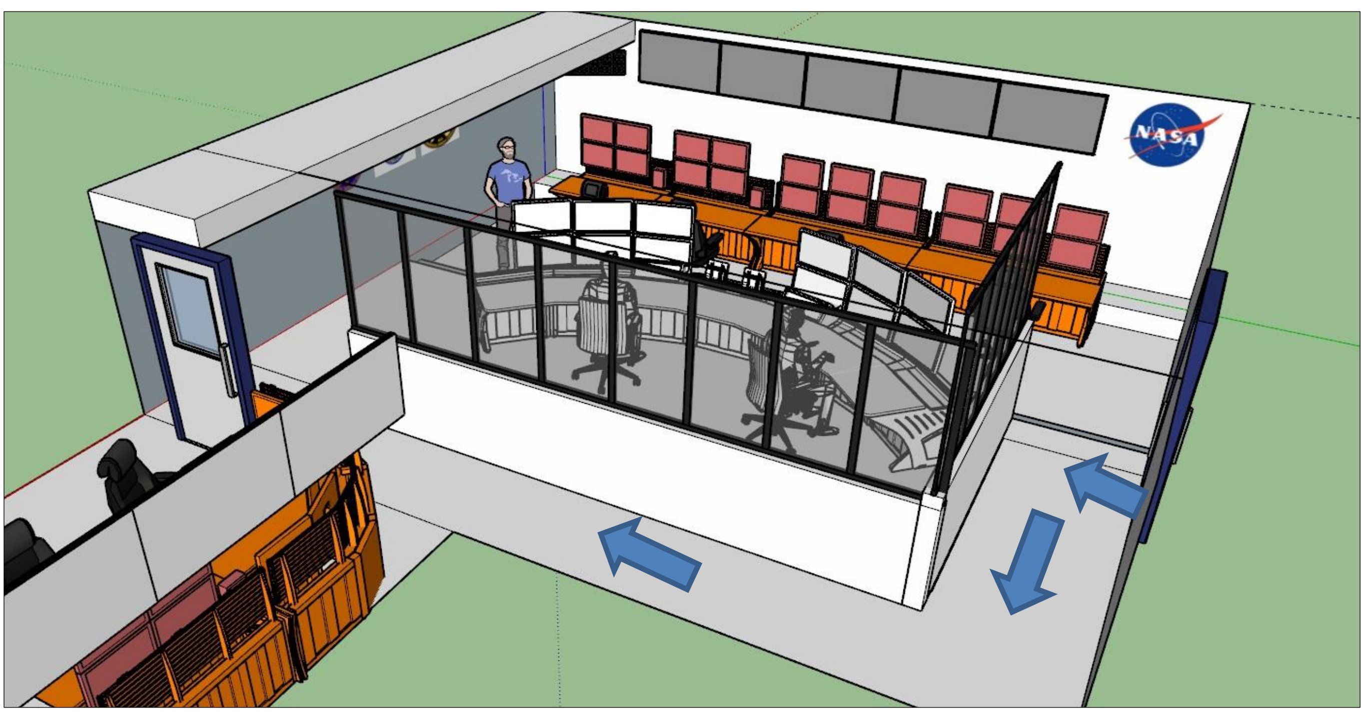

Figure 7.3-7. WFF Range Safety Room, Future Concept #3, View A

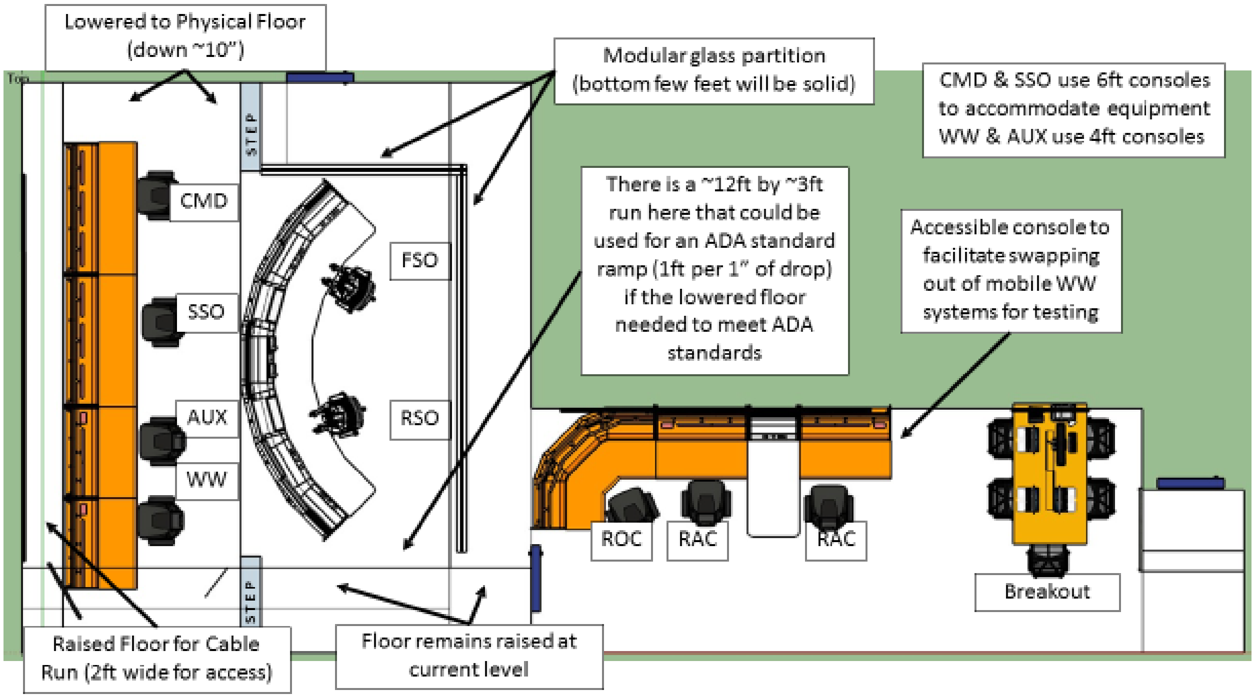

Figure 7.3-8. WFF Range Safety Room, Future Concept #3, View B

To better support launch customers, the WFF Range and Mission Management Office would like to be able to conduct up to four simultaneous or back-to-back launch missions in a seamless and safe fashion. In addition to supporting launch operations at WFF, Range Safety personnel support sounding rocket and balloon launches at remote locations. With the expectation of significantly increased operations, WFF personnel reported during interviews that they lack enough trained staff to sufficiently cover all expected operations, and they have no dedicated training devices to do so. The current operations tempo has allowed WFF to train in the Range Safety Room on the operational system. In contrast, VAFB performs 10–15 launches per year and reported that they experience difficulty with adequate training due to the operations tempo.

F-5. WFF currently uses the same system for training and operations.

F-6. WFF RSO operators reported that WFF lacks sufficient staff to support anticipated onsite and remote launch operations.

R-6. Ensure a means of supporting training without interfering with operations given the increase in operational tempo and increased need for trained operators. *(F-5, F-6)*

Concept #1 in Figure 7.3-5 addresses many of the needs mentioned (e.g., a dedicated training area and the capacity to run classified missions and simultaneous missions). WFF and Point Mugu are the only ranges with operators in a straight line. However, Point Mugu has only two personnel on console for launches, which facilitates coordination, collaborative decision-making, and being able to see the other operator's displays when needed. WFF operators have expressed a desire for a curved console to enhance collaborative decision-making; however, there is no algorithm, data, or standard to determine the optimal design of the Range Safety Room console set-up or to even prescribe whether the console should be straight or curved. Due to time criticality in launch operations, face-to-face communication is produced and interpreted in real time, because it affords visual, auditory, and gestural cues. Seeing others' actions enables personnel to infer meanings and clarify misunderstandings in a more effective and timely manner. An important aspect of crew coordination is the degree to which an operator can remain aware of what other members of the team are doing and be prepared to back them up. [ref. 8]. One of the salient attributes of proposed Concept #3 (see Figures 7.3-7 and 7.3-8) is that the designer has taken into account physical span of control, and therefore the leads are located above and behind the console positions they are leading.

During the NG-1 Antares launch, the preliminary study team noted that during pre-launch, just minutes from liftoff, the SO observed an off-nominal radar signal. There was an indication that an aircraft was in the red zone, but the signal seemed to come and go. The SO was observing and communicating while assessing whether a launch hold was needed. Additional personnel immediately entered the room, other Range Safety personnel left their seats, and everyone stood over the SO, who was performing this safety and time-critical task. The team noted that the area became rather noisy and crowded and a breakdown in communication was observed. The RSO and FSO were away from their consoles during this time to aid in group decision-making concerning the launch. Ultimately, the decision to scrub the launch averted any incident and the pilot was dealt with by the authorities.

Based on this example and the RockSat-X example described in Section 7.2.2, when an off-nominal event takes place pre-launch, even personnel from the MCR tend to enter the Range Safety Room, specifically around the displays and the console operator who has identified the issue. Even though it did not happen in the examples cited above, research of teams in safety-critical operations, has shown that such environments could lead to groupthink. Irving L. Janis, a social psychologist, coined the term *groupthink* in 1972 [ref. 9]. The term refers to a psychological phenomenon in which members of small, cohesive groups strive for consensus. Janis found that often people would ignore or refrain from stating their personal beliefs or adopt the opinion of the rest of the group, especially if they witnessed others valuing an opinion they did not share. Put simply, they chose to keep the peace rather than disrupt the uniformity. A number of factors can influence these behaviors. Groupthink tends to occur more often in situations where group members are similar to one another, and it is more likely to take place when a powerful and charismatic leader commands the group. Additionally, situations of extreme stress or where moral dilemmas exist also increase the occurrence of groupthink.

It is because of such situations that WFF desires to minimize or eliminate the presence of non-essential personnel in the Range Safety Room during launches when safety-critical tasks are being performed. During the assessment team's visits to CCAFS and VAFB, operators mentioned how vitally important reducing distractions was to allow them to focus on operations. CCAFS stated there is no access to the range safety room by customer personnel. Concept #3 (see Figure 7.3-7) has built in a walk path to direct the flow of those moving between rooms, but neither of the other concepts address this issue. At first glance, Concept #3 appears to have taken the right steps to manage the flow of personnel. But while the flow is managed, having a walk path may, in fact, encourage the behavior Range Safety personnel are trying to stop.

F-7. Range Safety operators reported the need for a distraction-free environment for operational efficiency.

R-7. Create a Range Safety Room design that minimizes distractions for operators. *(F-7)*

As stated, there is a strong need and desire to minimize the number of additional people in the Range Safety Room during launch operations. However, it may not always be possible to prohibit observers. Several Range Safety operators have indicated that they would prefer that visitors and observers be seated in the larger MCR room, since that room's occupancy during launch operations has decreased with the new Mission Operations Control Center opening. However, there is no agreement that this will be possible or even the preferred approach by those in management at WFF.

F-8. Based on observations at WFF and discussions at other ranges, current workplace design at WFF does not account for visitors and observers.

R-8. Ensure space and accommodations for visitors/observers are identified. *(F-8)*

Concept #1 is the only proposal that explicitly shows the WFF intent to create two Range Safety Rooms side by side to meet the demands of the expected increase in operations, the desire to run simultaneous or near-simultaneous operations, and the need for a classified facility. Although Concepts #2 and #3 do not show this explicitly, the following comments apply to any design that may be implemented.

The Concept #1 mirrored approach has operational issues, which require specialized training or risk increased operator errors due to situational awareness problems and delayed reaction times. For better crew resource management, the positions relative to each other should always be the same to maintain efficiency and mitigate risk of delays in taking actions or errors. If an operator works mostly in one of these rooms or is trained in one control room, then when working in the other location their brain will automatically want to perform tasks and operations in the same way they always have. Consider how those in the U.S. learn to drive a car from the left seat and how much adjustment is needed when driving from the right seat of an automobile. While driving from the left seat becomes automatic, changing to another position requires constant thought, analysis, and vigilance and slows responses.

In *Thinking, Fast and Slow*, Daniel Kahneman [ref. 10] describes "System 1" and "System 2" thinking. System 1 is "the brain's fast, automatic, intuitive approach," while System 2 is "the mind's slower, analytical mode, where reason dominates." He goes on to say that System 1 is more influential and in fact guides System 2 to a large extent. Also relevant to the WFF launch operations from Kahneman's work is the notion that a skill like math requires significant System 2 training before it becomes a System 1 skill. Similarly, the desire is for all operators on console with safety-critical, time-constrained tasks to use primarily System 1 thinking.

During the VAFB site visit, personnel indicated that the SSO station is not collocated with the operators, but in a separate room. They noted that this physical separation has caused challenges, and cautioned that if it were absolutely necessary for the SSO to reside in a different location, special considerations would be necessary to prevent adverse effects. In the Concept #2 design, the SSO position is on console with the RSO and FSO.

7.3.3 Other Range Safety Room Design Considerations

7.3.3.1 Classified Operations

As stated, WFF expects to begin performing classified operations within the next year. Procedural access restrictions to the Range Safety Room will not be sufficient, and WFF does not have the physical capability and security controls in place at this time to support classified operations. Additional considerations, per ICS 705-1 [ref. 11], for ensuring facility readiness for classified operations may include modifications to raise floors or drop ceilings in the area.

Another reference for creating the proper physical environment for classified operations is ICS 705 [ref. 12].

A Point Mugu SME stated that classified mission data sharing across channels is expensive, requires National Security Agency approval, and took their facility approximately 18 months to configure.

F-9. The Range Safety Room lacks access controls beyond those required for access to the Mission Operations Center in which the Range Safety Room is located.

O-3. WFF does not have the physical capability and security controls in place at this time to support classified operations.

R-9. Restrict access and visibility into the Range Safety Room through physical means. *(F-9, O-3)*

7.3.3.2 Large Shared Displays

Because of the potential tendency for an operator to become focused on detailed information or specific tasks at a compact workstation, a concern with workstation implementation is maintaining crew awareness of the overall situation and maintaining coordination of crew members. Most modern control room designs employing workstations also include large overview display panels, in part to address this concern. Large overview displays are spatially dedicated (fixed in position), continuously displayed (do not have to be selected or called up), and visible to the entire operating crew. They can aid in crew coordination by providing a common view and awareness of important status information. This also may help offset the tendency for an operator to become distracted with detailed information at one console. The RSO endeavors to remain cognizant of the big picture of the launch operation, and this shared overview display may provide assistance in doing so [ref. 13]. This will help to increase situational awareness for all Range Safety personnel on console for enhanced coordination and collaborative decision-making.

7.3.3.3 Lighting

Lighting is an issue identified and observed during the preliminary study and this NESC assessment. Due to the nature of the tasks being performed, appropriate lighting is critical. However, optimal lighting and the ability to read and interpret displays under certain lighting conditions are different for every person due to personal preferences, personal alertness, and differences in eyesight. Lighting needs could also change over the course of a single launch operation, since safety personnel can be called upon to report up to eight hours prior to launch. Changes in lighting could be due to eye strain, fatigue, external windows within the facility, or time of day. Due to reports from WFF safety personnel and NESC assessment team observations during launch, the assessment team took note of lighting at other benchmarked facilities. The VAFB Range Safety Room has dimmable overhead lighting at each control station, which can be customized by each operator without negatively affecting others on console [ref. 14].

Diffuse glare is caused by general environmental luminance levels, which can effectively reduce display contrast and make viewing difficult for users. These glare issues can be mitigated by adjusting display luminance levels, maintaining appropriate brightness levels in the control room, providing supplemental light at the workstation, and choosing the appropriate type of display [ref. 15].

Best practice mitigation strategies to minimize or eliminate glare in the Range Safety Room include:

a) Placing displays properly relative to light sources.

b) Using indirect lighting.

c) Using many dim light sources rather than a few bright ones.

d) Using anti-glare treatment, such as a diffusing surface or an optical coating (providing that it does not violate the requirements for luminance, contrast, and resolution of the displays or affect performance).

e) Filtering control of the light sources [ref. 15].

Additionally, the International Organization for Standardization (ISO) *11064-6:2005 Ergonomic Design of Control Centres* [ref. 16] requires lighting to achieve a Unified Glare Index (UGI) of less than 19 and a color rendering index (CRI) of more than 80. The CRI determines the perceived color of illuminated objects. If the CRI is low, this could hinder the perception of orange-colored objects. An incandescent bulb has a CRI of 100, which allows clear distinction between perceived colors. Therefore, this standard also indicates using triphosphor lights or fluorescent lights with a CRI over 90.

Table 7.3-1. Minimum Requirements for Control Room Lighting, from ISO 11064-6:2005

Control Room Measurable	Illuminance in Lux
Maximum illuminance for control rooms with video displays	500
Maintained minimum illuminance level	200

7.3.3.4 Noise

Another consideration for the Range Safety Room redesign process is noise level. While it is unlikely that noise will be an issue, it is important for designers and those procuring equipment to be sensitive to and aware of cumulative noise effects from new equipment. The cumulative ambient noise in the control room should not be above 65 decibels (dB), and every effort should be made to minimize noise distractions that could be generated inside or outside of the Range Safety Room. Standards and resources, such as MIL-STD-1474E [ref. 17] or the NUREG-0700 [ref. 18], are suggested by the NESC assessment team to serve as reference guides if there are concerns about designing to acceptable levels of unprotected hearing. The ISO 11064-6:2005 [ref. 16] recommends that the maximum ambient noise level for a control room be 45 dB. Therefore, a review of these standards indicates that a decibel level of 45–65 dB is appropriate for ambient noise levels.

F-10. Standards documents prescribe acceptable ambient noise levels for control rooms (e.g., MIL-STD-1474E, NUREG-0700, and ISO 11064-6:2005).

R-10. Ensure that ambient noise in the Range Safety Room, after equipment installation, is measured at no more than 65 dB. *(F-10)*

7.3.3.5 Spare Parts

The NESC assessment team observed an SSO monitor failure during the NG-10 Antares pre-launch operations. The assessment team noted no "hot" spares were available within the Range Safety Room. The replacement monitor did not work properly, and operators completed the operation without that display. Per the NUREG-0700, the Range Safety Room should contain or have very close access to expendable parts (e.g., light bulbs) and critical equipment spares that may be needed for launch operations. This storage should include an inventory and status records of spares, along with any tools that may be needed for installations or swaps [ref. 18].

F-11. During a launch, no hardware spares were available within the Range Safety Room.

R-11. Account for access to hardware spares and expendables during launch operations. *(F-11)*

7.3.3.6 Communications and Voice Recording

The existing WFF workspace layout separates the FSO and RSO to try to ensure, with no guarantee, that conversations between the two positions are conducted and recorded over the communication network in the event of the need to send destruct functions and perform post-destruct evaluations and analysis. Also, it has been noted that during pre-launch and off-nominal events, personnel may leave the console and congregate around a particular position. While the NESC assessment team was at VAFB, the discussion of communications and protocols was addressed. The VAFB SMEs described a recent event where they had to terminate a vehicle. VAFB conducts what they feel is robust training on console systems and on communication protocols. However, personnel were surprised during the after-destruct review to find approximately ~90% of the dialogue took place off the communication network and was not recorded. This runs counter to requirements that all ranges impose.

F-12. WFF management desires to have all voice communications recorded over the network in case of an off-nominal event.

R-12. Evaluate approaches to ensure all critical range safety communications are recorded. *(F-12)*

7.3.3.7 Personal Comfort

Quick access to food, restrooms, and similar facilities contribute to the operators' comfort, health, and performance. As stated in the WFF RCC Safety Room Layout White Paper, [ref. 19], the Range Safety personnel would like the ability to get food easily without having to leave the Range Safety Room to heat up food or retrieve food from a refrigerator. They often report for duty 8–10 hours prior to a launch, and they desire easy access to food and beverages, including coffee. WFF range safety operators indicated that their preference would be for the food/beverage area to be a separate room within the Range Safety Room to minimize distractions and smells. While the NESC assessment team agrees that these items would be convenient to have at ready access, a kitchen area, and restrooms are already close to the Range Safety Room. Of the three potential redesign options presented in Section 7.3.2, only one option includes a space for a small kitchenette. Therefore, the NESC assessment team notes the desire, but has elected not to suggest actions.

7.3.3.8 Personal Storage

During launch observations at WFF, the NESC assessment team noted the console areas were cluttered with input devices, headset cables, binders, laptops, and personal items. As discussed, supplemental space would allow operators to place personal or reference items away from the console, but within easy reach, to reduce clutter during launch operations.

F-13. Mandatory equipment and personal items created clutter on the Range Safety Room console areas during launch operations.

R-13. Provide a design solution to mitigate clutter on console during launch operations. *(F-13)*

7.3.4 Redesigned Range Safety Room Layout Summary

Based on best practices for Control Room design, the redesigned Range Safety Room design should preserve flexibility to allow future design modifications without imposing high demands on personnel for installation and maintenance. This design flexibility would include functional and physical modularity to accommodate replacements and upgrades, as well as spare physical capacity. Additional processing and electrical capacity would also be considered. These affordances will allow WFF to be prepared for increases in operations tempo, additional customers, and new launch platforms. Additionally, to keep up with emerging technologies and an evolving space market, it is reasonable to consider improving other launch-related rooms to support classified missions, dual operations, training, and ad hoc missions of opportunity. The above considerations are not an exhaustive list by any means.

7.4 Workstation Design

The workstation is the physical space where the operators perform their functions during launch activities. These typically are made up of the console itself; the benchboard, including racks for needed equipment; input/control devices; monitors for displays; communications equipment; and chairs. Input devices are covered in greater detail later in the report (see Section 7.5). Communications equipment will not be discussed in detail here, as WFF has already implemented the Mission Operations Voice Enhancement (MOVE) system. Further discussion of physical design concerns, lighting, and benchboard follows.

7.4.1 Workstation Physical Design Concerns

The operators' performance may be affected by design characteristics that affect reach, vision, and comfort. Unique considerations for these types of workstations include the following:

- Workstation height
- Benchboard slope, angle, and depth for consoles (i.e., accommodations for reach to controls or input devices; provision of writing space or space for launch binders).
- Control device location (i.e., placement of highest and lowest controls; distance from front edge of workstation).
- Display device location (i.e., placement of highest and lowest display devices, orientation relative to line of sight, viewing distance, position of frequently and infrequently monitored display devices).
- Lateral spread of control and display devices at a console or workstation.
- Clearances for legs and feet.

Since WFF has not designed or ordered new consoles, the best practice is to ensure that whatever console equipment is procured, the specifications meet the 5th percentile adult female and the 95th percentile male constraints per Table 7.4-1.

Table 7.4-1. Top-Level Standards for Workstation Design

Seated	Bounding Measurements (inches) 5th %ile Adult Female	95th %ile Adult Male[1]
Popliteal height (bend at back of knee)	15.0	19.2
Sitting height above seat surface (erect)	31.1	38.5
Sitting height above seat surface (relaxed)	30.5	37.6
Eye height above seat, sitting erect	26.6	33.6
Shoulder height above seat surface	19.6	25.8
Elbow height above seat surface	6.4	11.3
Functional reach	25.2	35.0
Extended functional reach	28.9	39.0
Thigh clearance height	4.1	7.4
Buttock-popliteal length	17.1	21.5
Knee height	18.5	23.6
Central body axis to leading console edge[5]	5.0	5.3
Eye distance forward of central body axis[5]	3.0	3.4

Source: NUREG-0700 [ref. 18]

For different design features, the designer would follow different guidelines as described above. For instance, when designing the console and control/display, no controls should be more than 25 inches from the front edge of the console surface in order to meet the 5th percentile female. Additionally, it is good practice to place no controls less than three inches from the front edge, to prevent inadvertent activation. For design features such as thigh clearance, one would use the 95th percentile male bounding measurement of 7.4 inches.

The operator at a console should be able to perform launch operation tasks with minimal to no repositioning. The amount of movement required will depend upon the arrangement of the controls and displays, laterally and vertically, on the console itself. The NESC assessment team noted that keyboards are not uniformly aligned with all user positions on console in the Range Safety Room. Users were observed twisting their bodies to use keyboards or look at monitors. Researchers noted that monitor and keyboard misalignment, leading to deviations from the neck's natural posture, can be detrimental to general musculoskeletal, upper body, and physical health [ref. 22].

F-14. The current WFF console requires repositioning or awkward positioning of the operator to perform tasks.

R-14. Ensure keyboard positioning accounts for proper anthropometrics and reach at operator workstation, to eliminate repositioning or awkward positioning. *(F-14)*

7.4.2 Workstation Lighting

Research conducted by the Health and Safety Executive in the UK [ref. 30] states that where individuals are carrying out different activities on consoles, they will need control over their local lighting. For example, a control and instrumentation engineer coming into a process control room lit at 300 lux may need a desk with a lamp to study a diagram or graphic display. Studies have shown that giving workers in open plan offices local control of lighting can increase job satisfaction (and decrease the experience of stress). This aligns with the feedback received from WFF Range Safety Room console operators, who reported the desire to have local lighting controls at their workstations, in addition to the following:

- Backlight behind monitors with dimmers to add additional ambient lighting control.
- Overhead lights with dimmers to add additional lighting control for users.

F-15. Research states that where individuals are carrying out different activities on consoles, they need control over their local lighting.

R-15. Include the ability for individuals on console to adjust the brightness at their workstations. ***(F-15)***

7.4.3 Benchboard

The benchboard will hold the rack-mounted controls that operators will use during launch procedures. This area between the console work surface and the displays will hold the MOVE system, the FTS panel, any other multi-function or hot keys that may be needed, and an input device, such as a joystick, etc.

Figure 7.4-1 WFF Current Console Benchboard and Work Surface

During pre-launch activities, each WFF range safety operator on console requires one or two binders of checklists and procedural information. While using these binders, the operators also interact with multiple systems at the console while preparing for launch and performing various checklist activities. The operators use laptops for secondary information coming through non-critical sources, keyboards and mice for data entry and display control, and the MOVE communications equipment. During launch, the NESC assessment team noted all these items crowding the current console work surface, which also includes the embedded FTS panel (Figure 7.4-1). [See section 7.3.3.8 for clutter information.] It is important to account for all constraints in the design of the console and benchboard. The operators will need ready access to the binders while still requiring unencumbered access and reach (Table 7.4-1) to everything on the benchboard without the risk of items on the work surface hindering access to, or causing inadvertent activation of, input devices. Figure 7.4-2 provides a view of the benchboard and work surface of the CCAFS console. The NESC assessment team noted that the use of binders on the work surface is not required at CCAFS. However, as can be seen in Figure 7.4-2, CCAFS operations would be impacted by binders or laptops on console in their current benchboard design. Binders or laptops placed on this approximately 13-inch-deep work surface could either hinder access to, or inadvertently activate, the joystick and function buttons on the bottom row of the benchboard. Simply adding depth to the work surface may not meet the needs and constraints of the operators on console, who must still be able reach across that work surface to access input devices. The design of the console must simultaneously meet all these objectives and constraints.

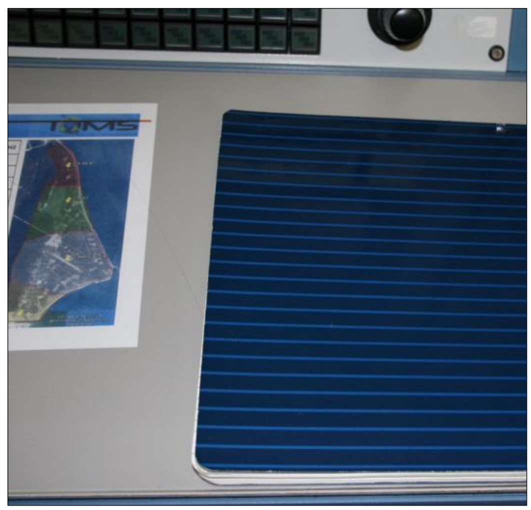

Figure 7.4-2. CCAFS Benchboard (left) and Console Work Surface (above)

WFF has purchased a new FTS and associated status and control equipment panels. The RSO and/or FSO will need access to the new FTS panel, which is the thin panel mounted between two FTS Status and Control panels. WFF RSOs reported that this will likely be installed at an angle on the benchboard in front of the RSO and FSO console positions. The new Command position will need multiple panels, and it is yet to be determined whether these will be mounted in an equipment rack, as shown in Figure 7.4-3.

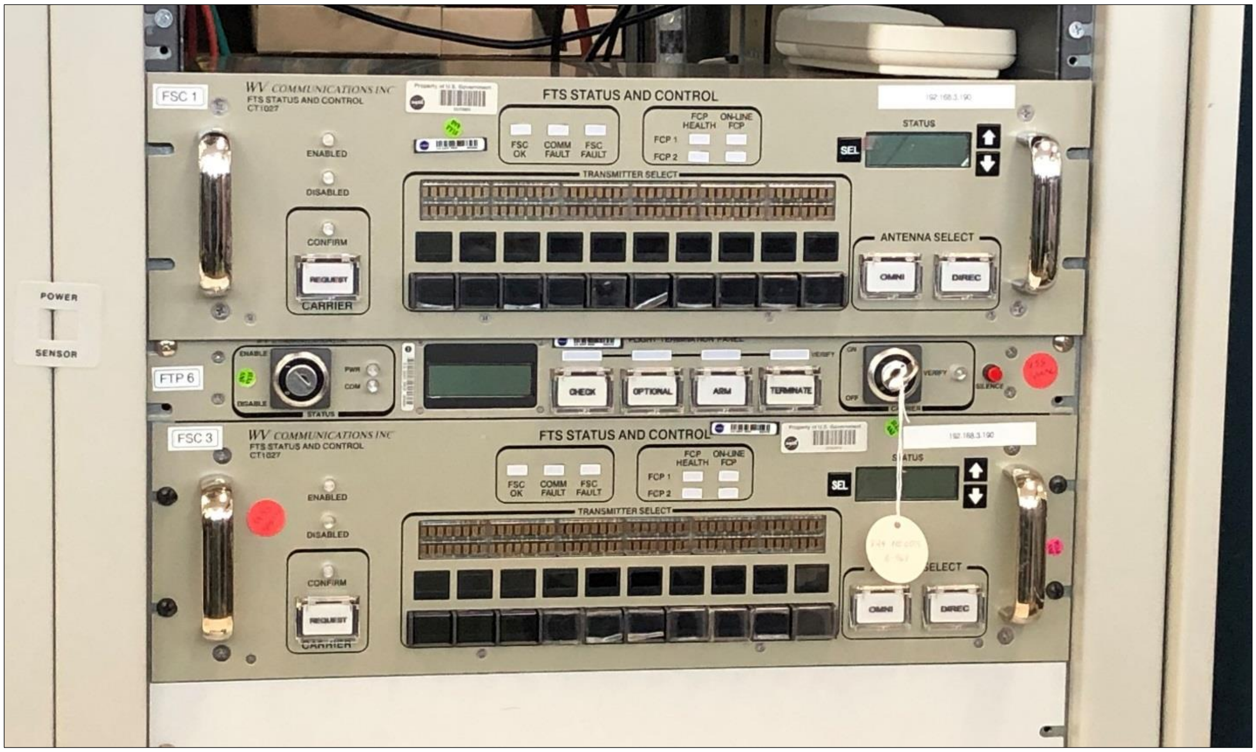

Figure 7.4-3 WFF New FTS and FTS Status and Control Equipment

7.5 Input Devices

The primary HF issues in selecting and evaluating input devices are usability and operational suitability. This means the input devices selected must be appropriate for the task. Also, where multiple data-input devices are used, they must be compatible and carefully integrated into the workstation design. This section discusses physical dimensions and suggested input devices design considerations; however, it is important to keep in mind that the compatibility between tasks and devices is critical for optimal task performance.

Input devices allow users—in this case the RSO, FSO, SO, and SSO—to transfer information to the RDDS that performs automatic computation and control functions. Information input can be continuous or discrete. Continuous input sets the system to a value along a continuum, e.g., by adjusting the brightness of a radar field of view. Discrete input devices select values from a finite set of alternatives, e.g., pushing the microphone button on and off. Selection of continuous or discrete input devices should be based on the range safety personnel's task objectives. [ref. 20].

The design arrangement and functioning of the controls influence system effectiveness and safety. Due to the many possible interactions between human, device, and technical systems on the WFF Range Safety Console, these devices cannot be regarded as machine elements. They must be selected on the basis of operational requirements as well as ergonomic criteria. To assist, the NESC assessment team has provided select design guidelines and considerations based on survey data collected during the preliminary HF study (see Appendix A), as well as observations and informal interviews the team conducted at WFF, VAFB, Point Mugu, and CCAFS.

Several issues could be considered in the design and use of input devices and the selection of equipment to meet the identified needs. Some of these issues are common across devices, while others are unique to the specific input device. Some common considerations are discussed first, followed by considerations unique to the various devices the operators on console in the Range Safety Room are likely to use in the future.

WFF Range Safety Console personnel use input devices in the form of keyboards, function keys, touchscreens, mice, and push buttons. Additional input devices, such as joysticks and trackballs, were observed by the NESC assessment team at the benchmarking locations that may be considered in the overall Safety Room redesign. Although the selection of a specific type of input device will depend upon the task at hand, in no case should the overall console upgrade require the operator to frequently switch between input devices. This was noted when the RSO, observed on console during Antares launch simulations in October 2018, leaned to the left to manually switch to Instantaneous Impact Point (IIP) display via keyboard input. Frequent switching between devices may contribute to an increase in operators' cognitive workload and potentially create a situation that can induce human error. The VAFB Range Safety Console design includes an automated this feature to switch between input devices, and users report it has improved ease of use.

The NESC assessment team observed, during simulated launch operations, that the RSO and FSO needed both hands on the keyboard and fingers on the appropriate three keys to make the display switch from Present Position Display (PPD) to IIP display prior to launch, due to how quickly the launch vehicle pitches over. As mentioned, the keyboards were not directly in front of the operators. The placement of hands and fingers while in an unnatural posture, as well as diverting attention to the displays for the rest of the countdown and launch to press the keys in time, could be problematic. Humans have limited attention available when two or more tasks are performed simultaneously. If task demands outweigh available attention, one or more tasks will suffer in performance speed or quality [ref. 21].

F-16. The current Mission Graphics System requires the RSO to manually switch to IIP display on a keyboard not directly aligned with that console position, requiring the user to divide attention resources.

R-16. Eliminate the need for users to shift attention during time- and safety-critical tasks. (F-16)

During observations and benchmarking activities at VAFB in September 2018, the NESC assessment team confirmed that Range Safety staff (MFCOs) use joysticks rather than keyboards as the preferred input method for tasks required prior to launch. However, the VAFB operators reported to the team that they prefer to remain hands-off after launch where possible. The WFF Range Safety Console personnel have been using keyboard and mouse input devices to control the majority of RDDS functions, which should be evaluated for clutter and other input/control options.

O-4. The WFF Range Safety Console configuration uses a series of keyboard and mouse combinations that create console workspace clutter.

O-5. VAFB operators report that they prefer to remain hands off, if possible, and allow their displays to pan zoom off the IIP display if it starts to significantly deviate from the nominal trace.

The following sections provide information and references that can be used for input device evaluation. They include sample HF best practice guidance to assist the WFF Range Safety Console upgrade project team in identifying appropriate input devices for the safety-critical tasks assigned to console personnel.

7.5.1 Keyboards

Keyboards are used in the Range Safety Room for data entry tasks prior to launch to configure the system. Users also make changes to the display formats using keyboard quick keys before and after launch.

The NESC assessment team observed multiple keyboards on console at once with no way to quickly distinguish which systems they controlled. As shown in Figure 7.5-1, as many as four keyboards are visible across two workstations.

Figure 7.5-1. WFF RSO and SO Workstations

F-17. Keyboards are used in the Range Safety Control Room for data entry tasks and display switching.

R-17. Ensure proper labeling is included in keyboard hot/quick key designs, if used. (F-17)

For use in future systems, keyboards are ideal for alphanumeric data entry, but not for many other functions. Ideally, a dedicated display control panel would enable quick selection of the desired displays, leaving the keyboards for alphanumeric data entry only. This is especially important for time-critical actions in the minutes immediately following launch.

The following HF guidelines apply to the design of any keyboard used in Range Safety operations.

- *Dynamic Characteristics*. The user should be able to reposition the keyboard. Keyboard slope should be 0–25 degrees above the horizontal plane (0–15 degrees is preferred; see Figure 7.5-1). Systems using multiple keyboards should have the same configuration for key layout. Feedback should indicate to the operator that a key was pressed. When users need to enter numerical data, a numerical keypad should be provided [refs. 18, 23, 26].
- *Function Keys.* Function keys should be clearly labeled and grouped on the keyboard in distinctive locations, in a layout compatible with their use. Frequently used or important functions should be in the most prominent or convenient locations. Frequently used functions should be executed by a single key press rather than combinations (e.g., “Ctrl+R” or others) [refs. 18, 25, 26, 31].
- *Single Method for Input.* Forcing users to shift from one keyboard to another should be minimized [ref. 18].
- *Inadvertent Operation.* Keys with major or destructive effects should be protected from inadvertent operation.
- *Equivalent Commands.* When menu operations can be completed by using “hot keys” on the keyboard, the keys should be listed next to the menu item.
- *Dimensions, Resistance, and Clearance.* Physical dimensions, resistance, and clearance on the work surface should meet the criteria given in MIL-STD-1472G [ref. 23].

7.5.2 Computer Mice

Computer mice are used on console at the WFF Range Safety Room to select menu items on screen to configure displays prior to launch. After launch, computer mice are not used unless some unexpected emergency necessitating their use arises. The likelihood of such an emergency is small, given other safeguards within the system.

Through the observation of users during launches and training sessions, the NESC assessment team noted multiple mice on console with no way to quickly distinguish which system they controlled. The team observed as many as four mice for one station—two identical pairs, each with a different function. Personnel on console were observed moving mice out of the way, tucking them out of reach, and storing them in keyboard trays to clear their workspace.

In addition, the large number of mice on console contributes to workplace clutter, leaving little room to operate the mice. This is especially true after manuals and documents, which users require, are also placed on the workspace. Consider reducing the number of mice and using a dedicated space for them, such as a keyboard and mouse tray, mounted under the console that runs the length of the workspace.

F-18. Keyboard and mouse system use could not be reliably and rapidly determined by Range Safety personnel when multiple sets were present at a given workstation.

F-19. As many as four separate keyboards and mice were at the SO station at once, with no way to accurately differentiate what system they controlled.

R-18. Streamline the number of input devices on console. (F-18, F-19)

The use of computer mice in developing future systems is not ideal for primary functions after launch, due to the unstable nature of computer mouse controls and their lack of "return to zero" capability. Computer mice may be used for auxiliary functions, such as zooming and panning the map, but developers should consider some means to return the view to center on the launch vehicle (e.g., a hard key for reset, or a timer function). Computer mice may also be used for non-critical functions, such as "tool tips" that provide additional information about on-screen items whenever the mouse pointer hovers over them. If tool tips are implemented, it is important that they not obscure mission-critical on-screen data.

The following HF guidelines apply when selecting or designing computer mice for use in range safety operations.

- *Dynamic Characteristics.* The mouse should be capable of moving freely throughout the XY space. The mouse requires a dedicated maneuvering surface/space. The alignment of the mouse and placement of maneuvering surface shall be within +/- 10 degrees of the correct orientation without visual reference to the controller. The mouse should easily move smoothly in any direction and should be operable with either the right or left hand [ref. 23].
- *Multiple Display Devices.* In systems that use multiple displays with a single pointing device, it is important that the user is able to easily track the cursor as it moves from one display to another [ref. 18].
- *Single Method for Input.* Forcing users to shift from one mouse to another should be minimized [ref. 18].
- *Consistency/Standardization.* The mouse should be used to access all necessary functions in all computer applications in the same way [ref. 14].
- *Menu Selection by Pointing.* When menu selection is a primary means of command entry, direct pointing should be provided [ref. 18].
- *Direct Pointing.* Pointing directly at a displayed option guarantees good display-control compatibility. A mouse should be available for selecting fields for direct entry of text [ref. 18].
- *Limb Support.* Support should be provided for hand, wrist, or arm whenever mice are used for precise or continuous movements [refs. 18, 24].
- *Dimensions and Button Characteristics.* Physical dimensions and mouse characteristics should meet the criteria given in MIL-STD-1472G [ref. 23].

7.5.3 Foot Pedals (Switches)

Foot switches are used in the Range Safety Room to facilitate hands-free, push-to-talk functionality for the communications system before and after launch. The foot switch provides a secondary means to achieve this functionality, in addition to the more commonly used handheld push-to-talk headset controller. The NESC assessment team observed, during several launches, that the foot switch was not always aligned with the user operating position, causing users to "hunt" for the switch with their feet. In addition, the foot switch design is such that it could tip over while in use, potentially leading to operational issues and distractions.

F-20. Foot switches for the communications system are not aligned with the user operating position, which increases the likelihood that the foot switch will tip over.

In future system design, foot switches can be used in much the same way as the current system. Foot switches have the potential to reduce operator workload and free hands for other critical duties.

O-6. Foot switches in the Range Safety Room provide a hands-free means of push-to-talk functionality with the potential to reduce operator workload.

The following HF guidelines apply when selecting or designing foot switches for use in range safety operations. The references in the bulleted list below contain additional information for foot pedal dimension, displacement, resistance, and separation for optimal use.

- *Dynamic Characteristics.* Foot switches may be used to balance the workload between multiple limbs, and are particularly effective at facilitating hands-free operation. Foot switches should be easily accessible and aligned with the ball of the user's foot. It is important that there are no nearby items on the floor that may obstruct operation. The switch surface and base should have a high degree of frictional resistance to prevent the foot switch from slipping [ref. 23].
- *Feedback.* The foot switch should provide the user with feedback that it has been actuated, such as a snap feel, audible click, or audio/visual feedback from another display [ref. 23].
- *Inadvertent Operation.* Foot switches are particularly susceptible to inadvertent operation, so their use should be limited to non-critical or infrequent functions [ref. 23].
- *Press-to-talk.* When foot switches are used in communications systems to facilitate press-to-talk functionality, hand-operated controls for the same functions should be provided in case of emergency operation, or when the operator needs to move to another location [ref. 23].
- *Dimensions, Resistance, and Displacement* Physical dimensions, resistance, and displacement of the foot switch should meet the criteria given in MIL-STD-1472G [ref. 23].

7.5.4 Touchscreens

Touchscreens are used in the Range Safety Room as a means for users to interact with the communications panel known as the MOVE Panel (Figure 7.5-2). Users can select which channel(s) they wish to listen to by selecting from square buttons arrayed in a grid on the touchscreen. Some settings (e.g., mute, system volume, etc.), are also controllable using this interface. WFF Range Safety does not intend to upgrade or modify the communications panel, so these general considerations are provided in case the use of touch screens is evaluated for the RDDS.

Figure 7.5-2. Touchscreen Used on Range Safety Console MOVE Panel

F-21. RSO team members can monitor verbal communications on up to 24 channels simultaneously, but receive no formal training on strategies or best practices for managing this task.

For use in future system redesign, touchscreens are ideal for "set and forget" functions, which are not used after launch. Touchscreens are not advised for safety-critical functions due to the potential for erroneous inputs [ref. 32]. This is especially important for functions executed after launch.

F-22. The WFF Range Safety Room is applying HF best practices in not employing touchscreens for safety-critical operations.

The following HF guidelines apply when designing touchscreens for use in range safety operations.

- *Dynamic Characteristics.* Touchscreens should not be used for applications that require prolonged inputs by the user, as this can lead to stress on the fingers and hand/arm fatigue over time. Touchscreens are prone to fingerprints, which may create difficulty reading important information on-screen. Touchscreens should be accessible to all users. GUIs for touchscreens should be designed for direct interaction, with minimal inputs required to complete frequently used functions. If touch inputs are used in conjunction with a cursor, cursor movement should follow smoothly along the XY plane with minimal latency [refs. 14, 18, 23].

- *Single Method for Input.* Forcing users to shift from touchscreen to keyboard or other pointing device should be minimized [ref. 18].
- *Inadvertent Operation.* Touchscreens are more prone to inadvertent actuation, and should not be used for safety critical functions [ref. 14].
- *Feedback for Multiple Workstations*. When multiple touchscreens are used simultaneously to influence a shared system, an audible beep or other feedback should be provided when a touchscreen action has been made [ref. 18].
- *Neutral Tint and Luminance.* If tint is applied to touchscreens, it should be neutral so as not to distort colors or interfere with color-coding. Luminance should be sufficient to allow the display to be clearly readable in the intended environment [ref. 18].
- *Dimensions, Resistance, and Separation of Touch Zones.* Due to finger size and parallax inaccuracy, a max height and width for touch zones should be 1.5 inches (40mm) and a minimum height and width of 0.6 inch (15mm), with a maximum separation distance of 0.25 inch (6mm) and minimum of 0.1 inch (3mm). Touchscreen resistance should be a maximum of 5.3 oz. (1.5 N) and a minimum of 0.1 in (3mm). More information on physical dimensions, resistance, and clearance with respect to touchscreens is available in MIL-STD-1472G [ref. 23].

7.5.5 Joysticks

Joysticks are not used at the WFF Range Safety Control Room, but they are in use at other range safety rooms (e.g., VAFB and CCAFS). Figure 7.5-3 is a sketch of the one observed on console at VAFB, which users reported liking for usability, ease of control, and efficiency. This joystick pivots and rotates, and each motion has a distinct purpose. The operator can pivot the joystick towards the mounting surface in four directions: up, down, right, and left. Pushing the joystick forward (i.e., away from the operator) pans the display north, while pulling the joystick in the opposite direction pans south. Left and right movements pan the displays east and west, respectively, and the joystick returns to the neutral position when released. In addition, zoom capability is available by rotating the joystick knob in one direction to zoom in and the opposite direction to zoom out. Pan and zoom are available by simultaneously twisting the knob and pivoting the joystick. If WFF is interested in pursuing the use of joystick control, the functions described above would be ones to consider in the design. In addition, the keyset controls should be configurable and preset prior to mission use.

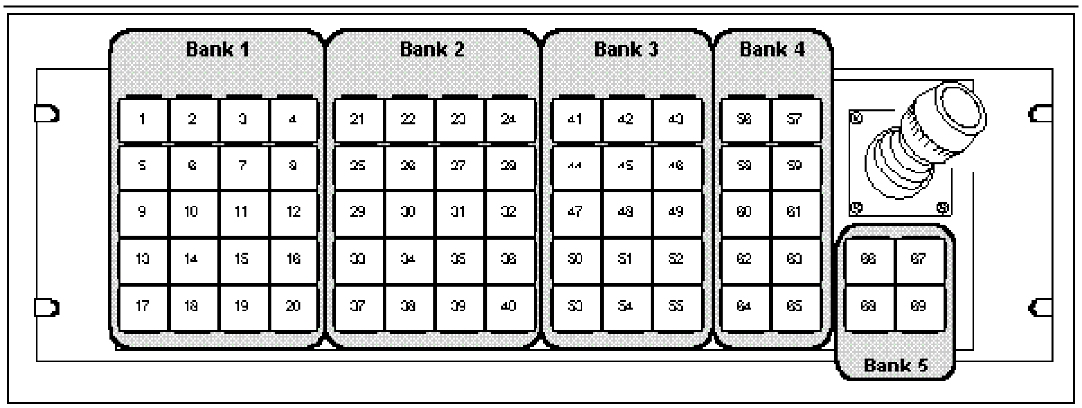

Figure 7.5-3. VAFB Joystick and Function Buttons

WFF RSOs reported that they would prefer a joystick option, including manual override capabilities, like that used on console at VAFB and CCAFS. However, the NESC assessment team noted that CCAFS was using real-time telemetry data vs. predicted nominal data to drive the pan/zoom trajectory data on screen. This resulted in a jerky trajectory display, also observed on the RDDS prototype, which was working on best available data. Auto pan and zoom, therefore, is best pulled from nominal trajectory data.

O-7. Auto pan and zoom can result in jerky movements on displays when nominal trajectory data are not used.

Through the observation of users, the NESC assessment team identified the following issues associated with the use of joysticks at other range safety facilities:

- Joysticks can be slower to respond to inputs than trackballs or mice without proper rate aiding.
- Joystick devices used for precision selections require a limb rest of some kind for the operators to steady themselves.

For future systems, joysticks may be used for functions that require gradual and steady cursor inputs. Joysticks can be used for pan/zoom functions due to their "return to center" capability. The term "return to center" refers to the inherent ability of the input device to physically return itself to a neutral position once the user has released it. Depending on the specific implementation, system designers must decide what corresponding display action occurs (if any) upon user release of the input device. Joysticks also can be used for pan/zoom functions, due to the precision with which a user can acquire a target. Joysticks can be problematic for quick selection tasks unless rate aiding is applied to bring their performance equal to that of computer mice or trackballs in this regard.

The following HF guidelines apply when designing a joystick for use in range safety operations. Additional design information regarding dimensions, resistance, displacement, clearance, and ergonomic mounting can be found in the references noted in the following list.

- *Dynamic Characteristics.* The joystick may be used when the task requires precise or continuous control in two or more dimensions. For applications where positioning accuracy is more important than speed (e.g., selecting a small moving object on-screen) an isotonic joystick should be used [refs. 18, 23]. In cases where speed is more important than accuracy (e.g., panning a map quickly), an isometric (or "stiff joystick") should be used [refs. 18, 23]. Maximum force required for full deflection of an isometric joystick should not exceed 27 pounds (118 N) [ref. 18]. Direction of cursor control should mimic the direction of joystick deflection (i.e., left cursor movement for left deflection of the joystick) [ref. 18]. Movement should not exceed 45 degrees from the center position, and should be smooth in all directions. Control ratios, friction, and inertia should meet the dual requirements of rapid gross positioning and precise fine position [ref. 18]. Positioning a cursor should be possible without noticeable backlash, cross-coupling, or need for multiple corrective inputs [ref. 23].
- *Fatigue.* Isotonic joysticks usually require less force to actuate than isometric joysticks and are less fatiguing over long periods of use [ref. 18].
- *Positive Centering.* Once the user is no longer deflecting the joystick, it shall return to center [ref. 23]. Isotonic joysticks used for rate control should be spring-loaded to return to center

when the hand is removed [ref. 18]. Isometric joysticks are the preferred choice when a precise return to center (zero) is required after the user removes their hand from the joystick [ref. 18].

- *Secondary Controls.* Isotonic joysticks may be used as mounting platforms for secondary controls, such as thumb- and finger-operated switches [ref. 18]. Inadvertent activation of secondary controls is less likely with isotonic joysticks as less force is required to actuate the device [ref. 18].
- *Limb Support.* Joysticks should be mounted to provide some form of limb support [ref. 23].
- *Dimensions, Resistance, and Clearance.* Physical dimensions, resistance, and displacement should meet the criteria given in MIL-STD-1472G [ref. 23].

7.5.6 Trackballs

Trackballs are not currently used on console at the WFF Range Safety Control Room, but they are in use at other range safety rooms (e.g., Point Mugu).

The NESC assessment team identified the following issues associated with the use of trackballs at other range safety facilities:

- Trackball devices have an increased potential to overshoot the desired selection target. This is especially evident on continuous pan/zoom operations.
- Trackball devices used for precision selections require a limb rest of some form.

For future systems, trackballs may be used for functions that require quick selection tasks. The use of trackballs for pan/zoom functions can be problematic, due to the potential for users to overshoot the intended target. In the event that a trackball was used for pan/zoom functions, a means should be provided to re-center the view on the launch vehicle (via a push button or other solution) to facilitate quick correction in the event of overshoot.

The following HF guidelines apply to the design of any trackball for use in range safety operations.

- *Dynamic Characteristics.* The trackball should be able to move the cursor in any direction without displaying any cross-coupling (i.e., cursor movement in the opposite direction). Cursor control ratios should permit both rapid gross positioning and smooth, precise fine positioning [refs. 18, 23].
- *Positive Centering.* If there is a "home position," the capability for an automatic return to that point should be provided [ref. 18].
- *Limb Support.* Support should be provided for the controller's wrist or arm when the trackball is used for precise or continuous movement [ref. 23].
- *Dimensions, Resistance, and Clearance.* Physical dimensions, resistance, and clearance on the work surface should meet the criteria given in MIL-STD-1472G [ref. 23].

7.5.7 Three-Dimensional Audio

Three-dimensional (3D) audio capabilities are not used in the WFF Range Safety Control Room, but the technology has the potential to reduce operator workload in communications applications. 3D audio can provide a directional sense for multiple audio channels, to aid users in identifying the source of the transmission.

Through initial research on the subject of 3D audio, the NESC assessment team found that 3D audio requires specialized equipment, which must be fully function-tested prior to every use. This testing can take slightly more time than a traditional communications system, although it is possible to employ an automated tone check. 3D audio is a fairly new technology, which may require additional troubleshooting on the part of users.

However, the NESC assessment team notes that 3D audio may be helpful for monitoring communications traffic, especially if it is modeled using spatially relevant patterns. In a multi-channel communications system, such as the MOVE, 3D audio can be helpful for identifying who is currently transmitting by using precision directional audio cues. This technology was reported as being helpful for operators on console at VAFB who were monitoring several communications channels at once. In addition, several WFF RSOs reported that chatter on the communications channel during the NG-10 Antares launch was distracting and caused decreased situational awareness. A 3D audio model could be based on the physical layout of a large room with many other radio operators, or an organizational hierarchy based on each radio operator's rank or authority level. The accuracy of identification could be further improved if the physical MOVE buttons and switches were laid out in a pattern to mimic the 3D audio model.

F-23. VAFB operators reported that 3D audio technology was helpful on console when simultaneously monitoring several communication channels.

F-24. WFF RSOs reported that chatter on communication channels during the NG-10 Antares launch was distracting and caused decreased situational awareness.

R-19. Consider use of 3D audio for monitoring multiple simultaneous communications frequencies. (F-23, F-24)

The following HF guidelines apply to the design of any 3D audio displays for use in range safety operations.

- *Dynamic Characteristics.* 3D audio displays are useful for applications in which the operator is highly tasked visually and the environment features numerous important spatial cues. 3D audio displays have been shown to enhance situational awareness, aid in separating multiple channels of information, and rapidly redirect the user's vision. For most applications, 3D audio should be presented in a two-dimensional format (i.e., all sound sources arrayed on a single plane in space) [Refs 14, 23].
- *Angular Separation.* The angular separation between discrete sound sources should be equal to or greater than 5 degrees in the horizontal plane or 10 degrees in the vertical plane to aid users in differentiating the source of the audio [ref. 23].
- *Binaural vs Monaural.* 3D audio cues should be presented binaurally and never monaurally [ref. 23].
- *Paired with Visual Cues.* 3D audio has been found to be most effective when paired with visual cues to reinforce the source of the information. For example, when being used to differentiate between transmission sources on a busy radio channel, a visual display that spatially mimics the aural display will enhance the users' situational awareness [ref. 14].

7.5.8 Push Buttons

Push buttons are used on console in the WFF Range Safety Control Room, primarily for the FTS. In the event that a destruct action must be taken using the current design, users lift the covers and depress buttons to send “Arm” and “Destruct” signals to the launch vehicle to terminate its flight. Push buttons are employed extensively at other ranges for many functions executed by using a keyboard at WFF.

F-25. WFF employs push buttons for the safety-critical FTS arm/destruct feature of the design panel, which is consistent with HF best practice.

Through the observation of personnel on console during launches and training, the NESC assessment team noted that the push button panels used for the FTSD are arrayed in a pattern that is not intuitive to the user, thus requiring extensive training given the safety-critical function of that system (see Figure 7.5-4).

Figure 7.5-4. Current FTS Panel Employing Push Buttons

The new FTS panel (Figures 7.5-5 and 7.5-6) has a simpler interface than the original panel.

The new FTS panel is a rack-mounted design, as opposed to the original FTS panel, which was inlaid into the user’s workspace. This changes the angle of the push buttons by 90 degrees, which necessitates ergonomic evaluation to ensure that the new panel causes no undue strain.

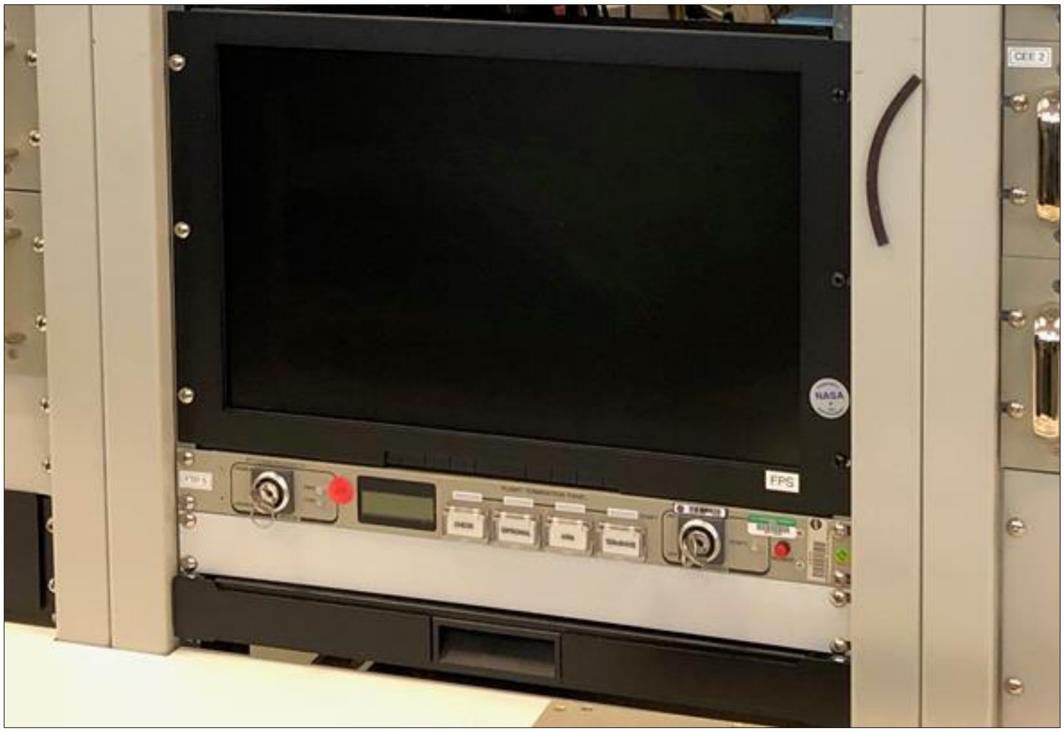

Figure 7.5-5. New FTS Panel in Rack

Figure 7.5-6. New FTS Panel, Detail

Figure 7.5-7. CCAFS Flight Termination Panel

Reprogrammable push buttons provide great flexibility, but come at the cost of potentially increasing operator workload and increasing the frequency of operator error whenever a button configuration has been changed. If the use of reprogrammable push buttons is desired in the new RDDS to build flexibility into the new system, additional user testing and verification will be necessary as new buttons/functions are added.

For future system design, push buttons may be used for functions that require fast action with positive feedback to complete. Push buttons can be used for display selection functions due to the speed, accuracy, and positive feedback they provide. Reprogrammable push buttons (as employed at CCAFS and VAFB) can provide long-lasting flexibility to the system, but care must be taken to frequently train operators immediately following any change to button configurations or layout.

The following HF guidelines apply to the design of any push buttons intended for use in range safety operations. Special design considerations for round and square push buttons, as well as for size, placement, and separation distances, are detailed in MIL-STD-1472G [ref. 23].

- *Dynamic Characteristics.* Push buttons should be arrayed with respect to the operator and positioned so they are easily accessible by the user. The layout of push buttons should conform to the tasks they are used to complete (via a task-driven sequence) or the displays with which they interact. Push buttons should be arrayed so workload is evenly distributed across limbs and no one limb is overburdened by normal use of the system. The most frequently used push buttons should be located in a position that is most prominent or convenient to the user. Push button arrays should follow a logical order for the user (e.g., sequential order that follows reading conventions – left to right or top to bottom) [refs. 18, 23].
- *Consistency.* Similar push buttons should function the same way across the system and regardless of operator station. Push buttons should be arrayed in a similar fashion across operator stations [refs. 18, 23].
- *Labeling.* Push buttons should be clearly labeled, so their functions can be understood by users at a glance [refs. 18, 25, 26, 31].
- *Slip Resistant.* The surface of the push button should be concave or coated in a slip-resistant material [ref. 18].
- *Single Method for Input.* Forcing users to shift from push buttons to keyboard should be minimized. [ref. 18].
- *Inadvertent Operation.* Push buttons with major or destructive effects should be located to prevent inadvertent operation and include covers to prevent unintentional actuation [refs. 18, 23].
- *Dimensions, Resistance, and Spacing.* Physical dimensions, resistance, and spacing for push buttons should meet the criteria given in NUREG-0700 and MIL-STD-1472G [refs. 18, 23].

7.5.9 Trade-off Evaluations for Selecting Input Devices

For Pointing Devices:

- Consider trade-offs when deciding whether to use a mouse or a touch screen to perform actions [ref. 27].

- Touch screens are not recommended if the task requires holding the arm up to the screen for long periods of time [ref. 18].
- The performance of all pointing devices is highly dependent upon the implementation and time spent refining details such as rate aiding and double-click speed. [ref. 14].

For Communications Equipment:

- Input devices selected should permit hands-free operation [ref. 23].
- Cords connecting devices should be non-kinking and coiled or retractable to prevent entangling controls or other objects in the work area [ref. 23].
- If a manual press-to-talk button is used, it should be usable by left- and right-handed operators [ref. 23].
- Backup equipment (such as a portable radio) should be provided in the event of an emergency that prevents the use of console equipment [ref. 18].
- Sending and receiving messages should be accomplished by explicit user action, with sufficient feedback to know that transmission has occurred [ref. 18].

7.6 RDDS Human-centered Automation

When designing a system that includes human users/operators and technology (hardware and software), tasks should be allocated in a way that combines human skills with automation to effectively and efficiently achieve task goals while also supporting human needs. One method for accomplishing this is function allocation, which can be used to determine whether a particular function or task should be accomplished by a human, technology, or a mix of both. This method typically involves a comprehensive process that accounts for technological feasibility, criticality of tasks, error rates, fatigue, costs, safety, hazards, human values and ethical issues, and human capabilities and limitations required to accomplish the tasks. Although a complete function allocation is the preferred methodology, it was not feasible due to the time and resource constraints of this activity.

Instead, a human-centered automation philosophy was implemented. "Human-centered automation" describes the use of automation technologies (e.g., intelligent aids, displays, input devices, and warning devices) to enhance the capabilities and compensate for the limitations of human operators responsible for the safety and effectiveness of complex dynamic systems [ref. 33]. This method was employed for this NESC assessment to assist the WFF Systems Software Engineering Branch in determining the best approach for allocating functions between automation and the humans on console, and this section represents the application of HF best practices for allocation of functions between humans and software with the primary purpose of enhancing user effectiveness and reducing human error.

The NESC assessment team used data collected from a heuristic evaluation, which is useful in this early stage of the system redesign. Heuristic evaluation involves HF experts examining the system and judging its compliance with recognized usability principles (i.e., heuristics). Involving multiple assessment team members improves the effectiveness of this method, and the NESC assessment team had up to five people collecting information, asking questions, and observing heuristics at all the benchmarking sites as well as during system operations and launches at WFF.

In addition, the NESC assessment team used stakeholder and user interview data collected during the preliminary study. That method provided a wide-ranging set of semi-structured interviews with personnel from the Range Safety Console to build a consensus about the problem statement. At that time, the HF preliminary study team created a set of questions regarding the RSO and FSO's roles, their needs, and metrics for project success. An overview of reported system usability from the preliminary study, applicable to Mission Graphics and RDDS upgrade functions, is summarized in Appendix A.

7.6.1 Analysis Approach

The allocation of functions to human and automation resources is determined by gaining a clear understanding of the context of use, task structure and demands; the knowledge required to perform the tasks; environmental constraints; functional and safety requirements; technological feasibility; and other relevant issues. This information can help determine whether each task is needed to accomplish the function and then decide whether it would be better allocated to humans or to functionalities designed into the Range Safety Console and RDDS. The NESC assessment team took an ad hoc approach to this function allocation.

One way to allocate functions to human and machine resources is by using prior experience gained from predecessor systems, such as those collected here using the existing Mission Graphics system. The ad hoc function technique allocates the existing system functions to hardware, software, and human-system components, based on predecessor systems and information about possible additional automation upgrades. The functions required of the existing system have been identified through sample function decomposition. The technique produces a sample function description of the system with recommendations based on research and best practices. The type and quantity of output should be updated as RDDS system complexity is identified and the extent of the changes matures.

Usability guidelines can help WFF ensure good usability is designed into the RDDS automation interfaces. Nielsen's usability heuristics are design principles against which a human system interface can be evaluated [ref. 34] and can be used for design guidance. In particular, the engineering principles found in Table 7.6-1 emphasize automation of unwanted workload and integration of data that attempts to shift the burden of information integration from the operator to the automation.

Table 7.6-1. Gerhardt-Powals' Cognitive Engineering Principles

Automate unwanted workload	Eliminate mental calculations, estimations, comparisons, and unnecessary thinking to free cognitive resources for high-level tasks
Reduce uncertainty	Display data in a manner that is clear and obvious to reduce decision time and error
Fuse data	Bring together lower level data into a higher level summation to reduce cognitive load
Present new information with meaningful aids to interpretation	New information should be presented within familiar frameworks (e.g., schemas, metaphors, everyday terms) so information is easier to absorb
Use names conceptually related to function	Display names and labels should be context-dependent, which will improve recall and recognition
Group data in consistently meaningful ways	Within a screen, data should be logically grouped; across screens, it should be consistently grouped. This will decrease search time
Limit data-driven tasks	Use color and graphics, for example, to reduce the time spent assimilating raw data
Include in the displays only that information needed by the operator at a given time	Exclude extraneous information that is not relevant to current tasks so the user can focus attention on critical data
Provide multiple coding of data	The system should provide data in varying formats and/or levels of detail to promote cognitive flexibility and satisfy user preferences
Practice judicious redundancy	To maintain consistency, it is sometimes necessary to include more information than may be needed at a given time

The approach discussed in this section is suited to the development of Range Safety Console equipment and associated systems as they evolve through several generations. However, the approach lacks standardization and traceability because the only evidence that the new system will perform is based on data available from the previous (existing) system. Given expected changes in personnel on console and associated duties, as well as the lack of maturity of the RDDS prototype, a comprehensive function allocation analysis was not performed.

Some general considerations for function allocation were considered, such as the role of personnel in maintaining situational awareness, monitoring system performance, or performing duties that only humans can perform, such as speaking and listening. Machines are better at responding quickly to signals, preforming precise routine (repetitive) operations, computing and handling large amounts of stored information quickly and accurately, and completing tasks that exceed human capabilities.

The current Mission Graphics System provides data to the operator on console, and often this data is lacking the context to make it readily usable information. Therefore, the data displayed often requires human analysis and continuous monitoring to be useful for decision-making. For instance, the battery voltages for the A and B sides are displayed on the FTSD. There are no color changes or alerts to indicate to the operator that the voltages have entered or are trending toward an unhealthy status. During launch and training observations, the NESC assessment team noted that the operators often use job aids (Figure 7.6-1) posted along the outside of the display to help with human analysis and decision-making, when this functionality could be embedded in the system.

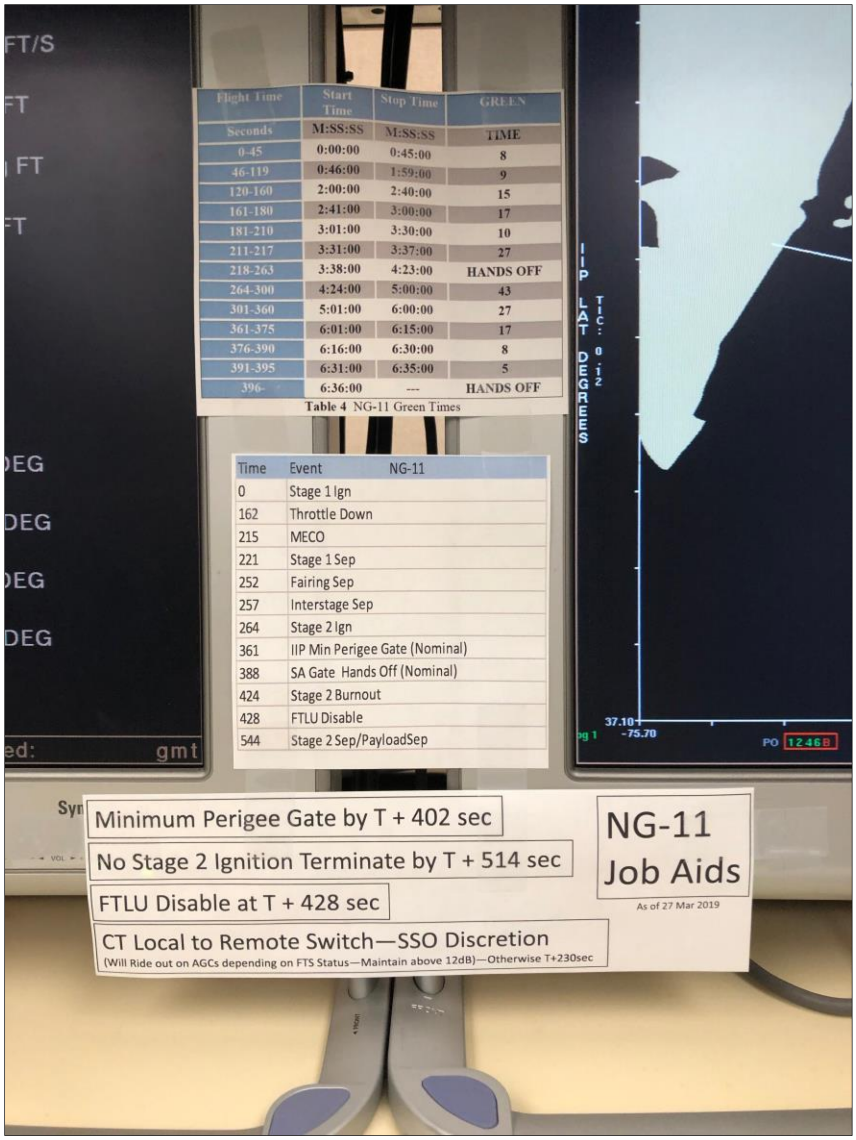

Figure 7.6-1. Job Aids on Console at WFF

F-26. WFF Range Safety personnel use job aids to assist with decision-making and situational awareness.

R-20. Provide readily available access to information on digital displays to minimize the need for analog job aids on console. (F-26)

The methodology used was adopted from research conducted by Endsley and Kaber [ref. 28], in which they formulated a taxonomy that identifies 10 levels of automation, distinguished according to human and machine roles in monitoring system status, generating strategies, selecting options, and implementing options. Table 7.6-2 provides a description of each level, with allocation roles.

Table 7.6-2. Endsley's Levels of Automation

Automation Level	Description
1) Manual	The human performs all tasks, including monitoring the state of the system, generating performance options, selecting the option to perform, and implementing it.
2) Action Support	At this level, the system assists the operator with performance of the selected action, although some human control actions are required. A teleoperation system involving manipulator slaving based on human master input is a common example.
3) Batch Processing	Although the human generates and selects the options to be performed, they then are turned over to the system to be carried out automatically. The automation is primarily in terms of physical implementation of tasks. Many systems, which operate at this fairly low level of automation, exist, such as batch processing systems in manufacturing operations or cruise control on a car.
4) Shared Control	Both the human and the automation generate possible decision options. The human retains full control over which option to implement; however, carrying out the actions is shared between the human and the system.
5) Decision Support	The automation generates a list of decision options, which the human can select from, or the operator may generate his or her own options. Once the human has selected an option, it is turned over to the automation to implement. This level is representative of many expert systems or decision support systems that provide option guidance, which the human operator may use or ignore in performing a task. This level is indicative of a decision support system that is capable of also carrying out tasks, while the previous level (shared control) is indicative of one that is not.
6) Blended Decision-Making	The automation generates a list of decision options, which it selects from and carries out if the human consents. The human may approve of the automation's selected option or select one from among those generated by the automation or the operator. The automation will then carry out the selected action. This level represents a high-level decision support system that is capable of selecting among alternatives as well as implementing the selected option.
7) Rigid System	This level is representative of a system that presents only a limited set of actions to the human. The human's role is to select from among this set and cannot generate any other options. This system is, therefore, fairly rigid in allowing the human little discretion over options. It will fully implement the selected actions, however.
8) Automated Decision-Making	The system selects the best option to implement and carries out that action, based upon a list of alternatives it generates (augmented by alternatives suggested by the human). This system, therefore, automates decision-making in addition to the generation of options (as with decision support systems).
9) Supervisory Control	The system generates options, selects the option to implement, and carries out that action. The human monitors the system and intervenes if necessary. Intervention places the human in the role of making a different option selection (from those generated by the automation or one generated by the human). This is representative of a typical supervisory control system in which human monitoring and intervention, when needed, is expected in conjunction with a highly automated system.
10) Full Automation	The system carries out all actions. The human is completely out of the control loop and cannot intervene. This level is representative of a fully automated system where human processing is not deemed necessary.

7.6.2 Function Analysis

7.6.2.1 Range Safety Officer

The RSO uses different sources to aid in decision-making during flight: visual input from the PPD and IIP display, radar and telemetry data via range data processing and display computers, video and metric optics sites, frequency monitoring, weather data (printouts received in hard copy form), ship and aircraft surveillance, skyscreen feedback, and flight mission rules. Figure 7.6-2 shows the RSO's console setup at WFF.

Figure 7.6-2. RSO screens on Console 1 at WFF

The current Mission Graphics System on console presents a situation in which the majority of tasks are at the *Manual Automation* level (Level 1), which means the RSO is responsible for performing all tasks of monitoring the state of the vehicle health and performance, generating options for vehicle tracking, selecting displays to monitor, and implementing necessary actions to maintain vehicle safety. Given the high workload during the safety-critical tasks performed during launch, the NESC assessment team advises that the RDDS be designed with varying levels of automation, depending on tasks, to aid in decision-making.

For instance, the RSO needs to take a manual action to switch displays between PPD and IIP when data on the PPD is no longer required for tracking the vehicle. Adding automation (Level 9, Supervisory Control) to this function on one of the display screens would allow the system to carry out the action while the RSO can monitor and take action if necessary.

F-27. Operators reported that mental workload is high when performing safety-critical tasks during launch operations.

R-21. Consider varying levels of automation to aid in decision-making. (F-27)

F-28. RSOs are required to manually switch displays during a time-critical operation.

R-22. Provide a means to eliminate manual switching of displays during launch operations. (F-28)

The PPD screen could remain visible to the RSO on another screen in case they wish to continue monitoring, although best practice would advise removing irrelevant information to avoid information overload and confusion.

Another function observed by the NESC assessment team and reported by users is the lack of PPD pan and zoom capability. The system tracks the vehicle in flight until it reaches the far corners of the viewing field on the PPD. It would provide more situational awareness if the RSO could track the vehicle along the flight path in a continuous motion (Level 9, Supervisory Control) as opposed to the current configuration.

VAFB MFCOs at VAFB reported that their IIP displays contain automatic pan and zoom tracking from time of vehicle launch, with the ability to manually override this function via button and joystick controls. They report that this is a desired feature allowing for ease of monitoring vehicle trajectory.

7.6.2.2 Flight Safety Officer (FSO)

In addition to having hard copy flight mission rules on console for reference, this functionality can be programmed into the RDDS to alert the FSO when mission rules have been breached and an arm/destruct action must be taken.

Throughout several observations of launches and training activities, the NESC assessment team observed three personnel on console using laptops as unofficial tools to aid in data analysis and calculations pertinent to flight. For example, at the NG-10 Antares launch in November 2018, the RSO and FSO were observed relying on external data concerning critical information, related to winds aloft in calculating nominal trajectory, which was to be sent via email. This information was received at T-3:30 minutes while staff was on console, forcing the FSO to monitor email while the range was green and entering terminal count. This is not an ideal scenario, not only due to the additional equipment causing workspace clutter, but also due to the inability to ensure that email servers would properly function in all scenarios, the additional stress and workload added to the FSO in getting access to that data, and the impending decision to turn the Range Safety Room into a classified space.

F-29. Critical launch acceptability and trajectory calculation information (e.g., winds aloft data) were received by secondary non-critical systems (e.g., email).

R-23. Reduce or eliminate reliance on secondary non-critical systems for critical launch information. (F-29)

7.6.2. 3 Surveillance Officer (SO)

The SO position is included here, although as noted, WFF is considering removing the SO from the Range Safety Room or eliminating the position. Regardless of the decision, further analysis will be needed, as that may adversely impact workload and responsibilities on console for the remaining Range Safety Room team. There is currently no WFF consensus on this decision.

It is important to note that the SO needs to maintain situational awareness on surveillance channels via the MOVE network communications system. The SO is responsible for keeping the RSO informed of surveillance activities that could affect the vehicle launch. The SO is responsible for monitoring the surveillance inputs for boats or aircraft within the launch area and assessing any associated risks to ensure public safety. Some of the WFF Range Safety personnel prefer having this safety position within the Range Safety Room to enhance situational awareness and coordination amongst the team on console during launch operations. Removing this safety insight and oversight from the Range Safety Room console could adversely affect RSO workload and level of situational awareness, which may compromise safety.

As described in Section 7.2.2, during the RockSat-X launch, the NESC assessment team observed the SO calculating risk hazard area and probabilities by hand to determine go/no-go when an 80-foot boat entered the launch area. Adding automation (Level 5, Decision Support) would alleviate the pressure on the SO to conduct calculations by hand in a time-sensitive situation with external influences and pressure to make a call. During the time frame of this assessment, the Range Safety Room console has implemented the use of an automated system that contains a risk calculation module to assist the SO with tasks on console pre-launch.

During the site visit with the VAFB MFCOs, the NESC assessment team learned that the surveillance operators (i.e., sea, air, and train) are in another room in their launch building. The MFCOs reported that, while not prohibitive, not being able to see the surveillance operators' displays or speak face-to-face if necessary decreased their situation awareness and inhibited their ability to gain clarity in a given situation. What VAFB has done to mitigate this is to send one of their safety analysts to sit next to the surveillance operators in the other room. This allows the safety analyst to quickly assess risks to any range fouler. Once analysts have assessed the risk to a range fouler, they report this to the MFCO in the Range Safety Room. VAFB has had to implement workarounds to maintain situation awareness regarding surveillance risks to launch due to SOs sitting in a location outside of the Range Safety Room.

With the planned increase in mission tempo forthcoming, the intent for the Range Safety Console to manage up to four Coyote missions at one time, and the added personnel constraints due to Range Safety staff supporting science balloon and sounding rocket launches around the world, adding supporting levels of automation into the existing and new RDDS capabilities is paramount to offset workload and increase efficiency.

7.7 RDDS Color and Luminance Considerations

7.7.1 Color

Following well-defined standards and HF best practices when designing and using color in display design is crucial to properly communicating status of the vehicle, and health of the system, which is a key factor in safety communications. These factors can affect the operator's understanding of what is happening during safety-critical tasks.

The advantages of color may seem apparent in system design; however, little attention is often devoted to the potential disadvantages of using color inappropriately, in this case with respect to complex cognitive aspects of the RSO environment. Color usage should be depicted in a manner that is perceptible and intuitive to the user at a first glance without hesitation, double-guessing, or confusion. It is imperative to maintain clear meaning and consistency across all displays. An understanding of why the colors were chosen, and the manner in which they are used, should be documented. This strategy is essential to the safety and efficiency of any launch mission.

Data were gathered through multiple efforts, including informal and formal knowledge elicitation with users during the Preliminary Study. During the preliminary study, several color-related issues were noted and initial requirements for color were developed (see Appendix A). This NESC assessment included observing the RockSat-X and NG-10 Antares launch missions, observing the RSO training course in August 2018, discussions with users during site visits to Point Mugu and VAFB in September 2018, observing Antares Rocket Launch crew training in October 2018, discussions with users during site visit to CCAFS in March 2019, and multiple visits to WFF.

In discussions with RSOs and observation, it was clear that the colors used in the current Mission Graphics displays follow no particular standards, and in fact some have double meanings. The inconsistency in color meaning, within and across displays, could lead to increased chance of misinterpretation upon quick glances or the possibility of confusion for trainees, possibly resulting in slowed response times or a high-impact, and potentially costly, mistake in a safety-critical environment.

F-30. Interviews, informal discussions with users, and RSO training showed that color considerations during the initial design of the Mission Graphics System were made without creating usability requirements or conducting formal testing for verification.

R-24. Engage an HSI practitioner to review, verify, and validate color selections on displays before critical design review. (F-30)

The NASA Ames Research Center Color Usage Laboratory [ref. 37] provides a guide to color design for information visualization. It includes information on the process for designing for color usage in interface graphics; examples of display designs; a color selection tool; information about color usage standards and guidelines; and references resources. Aerospace graphics are the primary focus of this online resource, but much of the information is useful and relevant for guiding color usage within the RDDS for WFF. Six overarching guidelines for color discrimination and identification are identified, based on scientific research, best practices, and government and industry standards. These are:

1. Use no more than six colors to label graphic elements.
2. Use colors in conformity with conventional standards.
3. Use color coding consistently across displays and pages.
4. Use color coding redundantly with other graphic dimensions to account for differences in color vision.
5. Avoid color coding on small graphic elements. Color discrimination is better for large areas than for small (e.g., small fonts and symbols). This is more of a concern for “at-a-glance” applications than for those where careful examination is possible. Even in the latter, it can slow the user down.
6. Use neutral gray surrounds where color judgments are critical.

Although these overarching guidelines follow best practices, they should not be viewed as requirements. For example, Guideline 2 specifies conformity with conventional standards, such as red for stop/danger/action needed; amber for caution/attention needed; and green for good/go/normal. However, not every industry adheres to the same color conventions. These colors do not always have the same meaning in the nuclear industry, for instance [ref. 34]. It is important that developers and operators choose a color convention that best fits their needs and verify the meaning of each color chosen, then document this in a color style guide, as noted in Appendix A [ref. 23].

Multiple instances where the use of color did not follow Guidelines 2 and 3 above were found across all Mission Graphics displays and captured in the requirements in Appendix A. One example of maintaining consistent color between displays can be observed on the Primary Position Display (PPD) (Figure 7.7-1) and the IIP display (Figure 7.7-2). These two displays, which are the primary screens that the RSO and Flight Safety Officer (FSO) use during safety-critical launch missions, represent the destruct lines in a magenta color, which, if a vehicle crosses (IIP, Figure 7.7-2) or becomes parallel to the line (PPD, Figure 7.7-1), denotes a "destruct" action is necessary. However, these two displays also show a lack of consistency in color usage. The color white on the PPD is used to define multiple meanings. On the left side of the PPD, the white line down the middle signifies nominal trajectory; however, on the right side of the display, white signifies both nominal trajectory and the "inverse velocity vs. time" line. This latter example was noted by range safety operators during the preliminary study; they stated that understanding what the displays are showing in the current Mission Graphics system requires experience. The use of color on these displays represents display elements and is not used to alert the user to an action or an alert of any kind. During the RSO training course in August 2018, the instructor mentioned that the destruct lines on the displays should be red, since the destruct lines represent danger, specifically an off-nominal course, indicating to the user that a "destruct" action is necessary. Although the topic of color was mentioned in passing, the meaning of each color on the displays is not discussed during the RSO training course, which is geared towards the system as a whole and open to RSOs from multiple ranges, all of which have different color usage mechanisms.

O-8. Use of color is not consistent across the benchmarked ranges.

O-9. The meaning of display colors is not covered in the RSO training course.

R-25. Include display color conventions for all relevant ranges in the RSO training curriculum. *(O-8, O-9)*

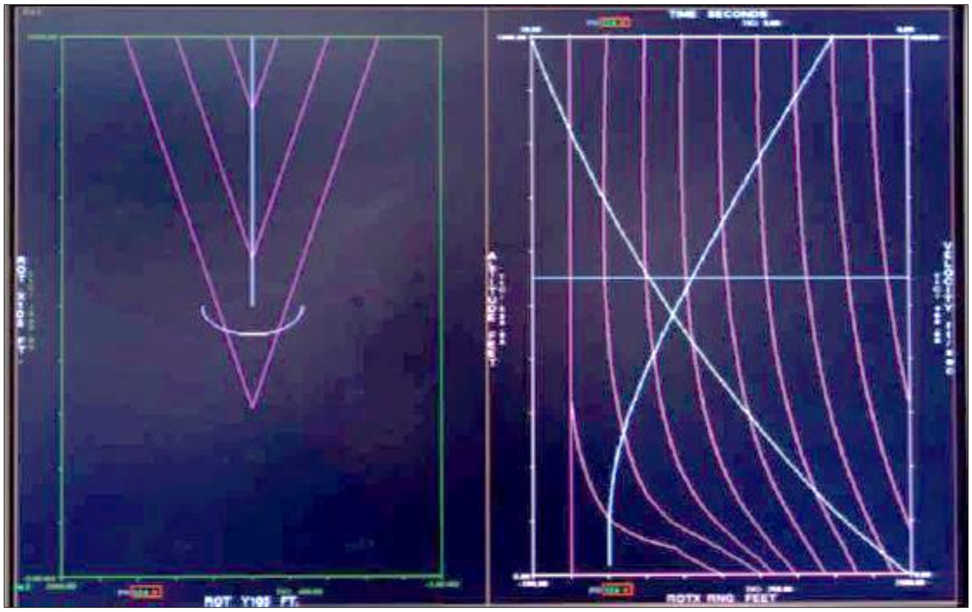

Figure 7.7-1. Present Position Display

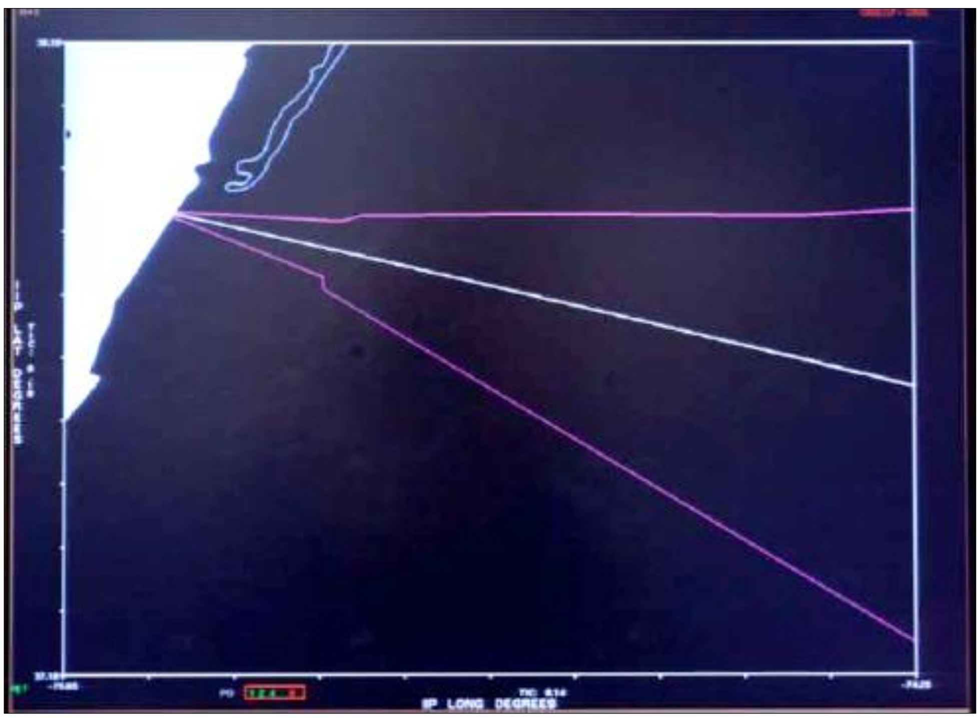

Figure 7.7-2. Instantaneous Impact Point Display

Also, it is important to note that with respect to Guideline 4, concerning the use of color with other graphic dimensions to account for differences in color vision, that all concerns regarding design for users with color blindness are addressed by current mandatory NASA physical requirements for these positions. Therefore, design considerations for this are not an issue and compliance with The Rehabilitation Act of 1973 [ref. 38] is not needed.

7.7.2 Luminance

Luminance can be defined as the "physical measure of the amount of light emitted or reflected in a given direction in a display" [ref. 15].

Luminance should be considered constant throughout all critical displays used in the Range Safety Room, including displays used for training, wind weighting, and testing.

Additionally, for the sake of this document, the following terms are defined as follows:

- **Contrast**: The difference in luminance or color that makes an object (or its representation in an image or display) distinguishable.
- **Chromaticity**: An objective specification of the quality of a color, regardless of its luminance.
- **Foot-candle** (fc): The luminance on a one-square-foot surface, of which there is a uniformly distributed flux of one lumen.
- **Foot-lambert**: A measure that has been corrected for the visual system's differential sensitivity to different wavelengths, approximating perceived brightness [ref. 15].
- Saturation: Intensity of color in an image.

Luminance levels can affect how the brain perceives color, sometimes causing colors to be perceived as a different color, especially if the luminance values (measured in foot-candles or foot-lamberts) are within a certain range, which is why considering the impact of luminance when choosing a color scheme is important. Luminance, however, affects not just color but also the user's ability to properly view symbols and text. It can even affect a person's eyesight if the brightness level of the displays is too high or too low.

When designing for color, background and foreground luminance levels should account for the user's ability to easily discriminate foreground color from background color. Designing for color also needs to consider the type of displays to be used and the settings available for those displays. For instance, some displays automatically increase in brightness under certain lighting conditions (similar to an iPhone that automatically brightens or dims the screen based on lighting conditions). Although these settings may be appropriate for a cell phone, they may not be suitable in a control room environment, and could have consequences in how color is visualized and its effects on users' vision.

Visual displays should provide clear information that a user can understand at first glance. The main criteria to consider in regards to luminance contrast are the luminance of symbols, text, graphics, etc. relative to the rest of the display [ref. 36]. For example, the salience of the dot that symbolizes the vehicle in the current primary RSO displays relies on the contrast level relative to the color and luminance of the display background. Similarly, the salience of the destruct lines relies on the relative luminance of the display background. These examples are another reason to design color with an understanding of which color combinations to avoid. In addition to salience, legibility of text (along with font size) is affected by luminance and contrast. For example, discussions with operators indicated that the text on the IIP display (Figure 7.7-2) is difficult to interpret, especially at a quick glance, due to the contrast between the foreground and background colors. Designs that do not account for color luminance and contrast not only cause interpretation issues, but also strain users' eyes. Luminance and contrast, in addition to color combinations to avoid, need to be considered throughout the design process.

F-31. User interviews indicated that the text on the IIP display is difficult to interpret due to the luminance and contrast.

R-26. Account for color, luminance, and contrast in the RDDS design. *(F-31)*

Color luminance and contrast refers to "the relationship between symbol and background associated chromatic differences such as hue and saturation" [ref. 35]. Chromaticity desaturation effects when using specific colors, such as red, on a display, should also be considered; chromaticity desaturation, which can make the color red appear white, can cause misunderstanding when a user quickly glances at a display to obtain critical information regarding the status of the launch or the health of a vehicle. [ref. 15].

Designers should also avoid the following color combinations: [ref. 32]

- Saturated red and blue
- Saturated blue and green
- Saturated red and green
- Saturated yellow and green
- Yellow on purple
- Yellow on green
- Green on white
- Blue on black
- Magenta on green
- Red on black
- Magenta on black
- Yellow on white

Colors used for display elements, including text, should be distinguishable, not only in meaning but also in luminance contrast, and should not blend in with the background.

8.0 Findings, Observations, and NESC Recommendations

8.1 Findings

The following findings were identified:

General HSI

F-1. The WFF Range Safety Operations Office has no HSI practitioner on staff to help integrate RDDS and Range Safety Room equipment layout for safe and efficient operations.

F-2. HSI analysis of the RDDS design has not been performed.

F-3. No overarching WFF standard operating procedure exists.

Range Safety Room Layout

F-4. The FSO and RSO are separated, with two consoles and operators between them.

F-5. WFF currently uses the same system for training and operations.

F-6. WFF RSO operators reported that WFF lacks sufficient staff to support anticipated onsite and remote launch operations.

F-7. Range Safety operators reported the need for a distraction-free environment for operational efficiency.

F-8. Based on observations at WFF and discussions at other ranges, current workplace design at WFF does not account for visitors and observers.

F-9. The Range Safety Room lacks access controls beyond those required for access to the Mission Operations Center in which the Range Safety Room is located.

F-10. Standards documents prescribe acceptable ambient noise levels for control rooms (e.g., MIL-STD-1474E, NUREG-0700, and ISO 11064-6:2005).

F-11. During a launch, no hardware spares were available within the Range Safety Room.

F-12. WFF management desires to have all voice communications recorded over the network in case of an off-nominal event.

F-13. Mandatory equipment and personal items created clutter on the Range Safety Room console areas during launch operations.

Workstation Design

F-14. The current WFF console requires repositioning or awkward positioning of the operator to perform tasks.

F-15. Research states that where individuals are carrying out different activities on consoles, they need control over their local lighting.

Input Devices

F-16. The current Mission Graphics System requires the RSO to manually switch to IIP display on a keyboard not directly aligned with that console position, requiring the user to divide attention resources.

F-17. Keyboards are used in the Range Safety Control Room for data entry tasks and display switching.

F-18. Keyboard and mouse system use could not be reliably and rapidly determined by Range Safety personnel when multiple sets were present at a given workstation.

F-19. As many as four separate keyboards and mice were at the SO station at once, with no way to accurately differentiate what system they controlled.

F-20. Foot switches for the communications system are not aligned with the user operating position, which increases the likelihood that the foot switch will tip over.

F-21. RSO team members can monitor verbal communications on up to 24 channels simultaneously, but receive no formal training on strategies or best practices for managing this task.

F-22. The WFF Range Safety Room is applying HF best practices in not employing touchscreens for safety-critical operations.

F-23. VAFB operators reported that 3D audio technology was helpful on console when simultaneously monitoring several communication channels.

F-24. WFF RSOs reported that chatter on communication channels during the NG-10 Antares launch was distracting and caused decreased situational awareness.

F-25. WFF employs push buttons for the safety-critical FTS arm/destruct feature of the design panel, which is consistent with HF best practice.

RDDS Human-centered Automation

F-26. WFF Range Safety personnel use job aids to assist with decision-making and situational awareness.

F-27. Operators reported that mental workload is high when performing safety-critical tasks during launch operations.

F-28. RSOs are required to manually switch displays during a time-critical operation.

F-29. Critical launch acceptability and trajectory calculation information (e.g., winds aloft data) were received by secondary non-critical systems (e.g., email).

RDDS Color and Luminance Considerations

F-30. Interviews, informal discussions with users, and RSO training showed that color considerations during the initial design of the Mission Graphics System were made without creating usability requirements or conducting formal testing for verification.

F-31. User interviews indicated that the text on the IIP display is difficult to interpret due to the luminance and contrast.

8.2 Observations

The following observations were identified:

Operations and Personnel

O-1. WFF training material, Module 1 Roles and Responsibilities, does not match the operational practices of the RSO and FSO as observed during simulated training and launches.

General HSI

O-2. During launch simulation training, the WFF RSOs did not follow a standardized communication protocol.

Range Safety Room Layout

O-3. WFF does not have the physical capability and security controls in place at this time to support classified operations.

Input Devices

O-4. The WFF Range Safety Console configuration uses a series of keyboard and mouse combinations that create console workspace clutter.

O-5. VAFB operators report that they prefer to remain hands off, if possible, and allow their displays to pan zoom off the IIP display if it starts to significantly deviate from the nominal trace.

O-6. Foot switches in the Range Safety Room provide a hands-free means of push-to-talk functionality with the potential to reduce operator workload.

O-7. Auto pan and zoom can result in jerky movements on displays when nominal trajectory data are not used.

O-8. Use of color is not consistent across the benchmarked ranges.

O-9. The meaning of display colors is not covered in the RSO training course.

8.3 NESC Recommendations

The following NESC recommendations are directed to the WFF Range and Mission Management Office and the Software Engineering Branch.

General HSI

R-1. Engage an HSI practitioner to work concurrently across project offices and alongside RSOs and members of the Systems Software Development Branch, as needed, to ensure human operations operator capabilities and limitations are effectively addressed throughout the Range Safety Room redesign effort and project life cycle. ***(F-1)***

R-2. Apply HSI considerations and NASA system requirements guidance throughout the project life cycle. ***(F-2)***

R-3. Investigate whether operational efficiencies could be obtained by developing an overarching standard operating procedure for WFF Range Safety Operations. ***(F-3)***

R-4. Develop a comprehensive recurrent training program to improve operational adherence to standardized console processes and communications included in the RSO Training Modules. ***(O-2)***

Range Safety Room Layout

R-5. Position displays to enable coordinated decision-making and cross-checking between the RSO and FSO. ***(F-4)***

R-6. Ensure a means of supporting training without interfering with operations given the increase in operational tempo and increased need for trained operators. ***(F-5, F-6)***

R-7. Create a Range Safety Room design that minimizes distractions for operators. ***(F-7)***

R-8. Ensure space and accommodations for visitors/observers are identified. ***(F-8)***

R-9. Restrict access and visibility into the Range Safety Room through physical means. ***(F-9, O-2)***

R-10. Ensure that ambient noise in the Range Safety Room, after equipment installation, is measured at no more than 65 dB. ***(F-10)***

R-11. Account for access to hardware spares and expendables during launch operations. ***(F-11)***

R-12. Evaluate approaches to ensure all critical range safety communications are recorded. ***(F-12)***

R-13. Provide a design solution to mitigate clutter on console during launch operations. ***(F-13)***

Workstation Design

R-14. Ensure keyboard positioning accounts for proper anthropometrics and reach at operator workstations, to eliminate repositioning or awkward positioning. ***(F-14)***

R-15. Include the ability for individuals on console to adjust the brightness at their workstations. ***(F-15)***

Input Devices

R-16. Eliminate the need for users to shift attention during time- and safety-critical tasks. ***(F-16)***

R-17. Ensure proper labeling is included in keyboard hot/quick key designs, if used. ***(F-17)***

R-18. Streamline the number of input devices on console. ***(F-18, F-19)***

R-19. Consider use of 3D audio for monitoring multiple simultaneous communications frequencies. ***(F-23, F-24)***

RDDS Human-centered Automation

R-20. Provide readily available access to information on digital displays to minimize the need for analog job aids on console. ***(F-26)***

R-21. Consider varying levels of automation to aid in decision-making. ***(F-27)***

R-22. Provide a means to eliminate manual switching of displays during launch operations. ***(F-28)***

R-23. Reduce or eliminate reliance on secondary non-critical systems for critical launch information. ***(F-29)***

RDDS Color and Luminance Considerations

R-24. Engage an HSI practitioner to review, verify, and validate color selections on displays before critical design review. ***(F-30)***

R-25. Include display color conventions for all relevant ranges in the RSO training curriculum. ***(O-8, O-9)***

R-26. Account for color, luminance, and contrast in the RDDS design. ***(F-31)***

9.0 Alternative Viewpoint(s)

No alternative viewpoints were identified during the course of this assessment by the NESC team or the NESC Review Board (NRB) quorum.

10.0 Other Deliverables

No deliverables were produced beyond this report and associated observations, findings, and NESC recommendations.

11.0 Lessons Learned

No lessons learned were identified as a result of this assessment.

12.0 Recommendations for NASA Standards and Specifications

No recommendations for NASA standards and specifications were identified as a result of this assessment.

13.0 Definition of Terms

Finding	A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation.
Human Factors	HFE is defined in the HSI Practitioner's Guide as designing hardware and software to optimize human well-being and overall system safety, performance, and operability by designing with an emphasis on human capabilities and limitations as they impact and are impacted by system design across mission environments and conditions (nominal, contingency, and emergency) to support robust integration of all humans interacting with a system throughout its life cycle. HFE solutions are guided by three principles: system demands shall be compatible with human capabilities and limitations; systems shall enable the utilization of

human capabilities in non-routine and unpredicted situations; and systems shall tolerate and recover from human errors.

Human Systems Integration

Human Systems Integration (HSI) is defined in NPR 7123.1B as an interdisciplinary and comprehensive management and technical process that focuses on the integration of human considerations into the system acquisition and development processes to enhance human-system design, reduce life cycle ownership cost, and optimize total system performance. HSI design activities associated with operations, training, human factors engineering, safety, maintainability and supportability, habitability, and survivability are considered concurrently and integrated with all other systems engineering design activities. The HSI process is critical due to the complexity of the integration needed in order to facilitate safe and efficient operations.

Lessons Learned — Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure.

Observation — A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.

Recommendation — A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk.

Safety — Safety factors ensure the execution of mission activities with minimal risk to personnel. Mission success includes a safe range safety crew, public, and surrounding areas following completion of mission objectives and maintaining the safety of all ground personnel.

14.0 Acronyms and Terminology

AFSO	Assistant Flight Safety Officer
AFTS	Automated Flight Termination System
ACDS	Advanced Command Destruct System
ACO	Aerospace Control Officer
CCAFS	Cape Canaveral Air Force Station
CMD	Command System Controller
dB	decibels
DFO	Distant Focused Overpressure
DoD	Department of Defense

ELV	Expendable Launch Vehicle
FO-G	Forward Observer Ground
FSA	Flight Safety Analyst
FSO	Flight Safety Officer
FSPO	Flight Safety Project Officer
FTS	Flight Termination System
FTSD	Flight Termination System Display
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GUI	graphical user interface
HF	Human Factors
HFE	Human Factors Engineering
HSI	Human Systems Integration
IIP	Instantaneous Impact Position
IRIS	Interface Region Imaging Spectrograph
LaRC	Langley Research Center
LST	Launch Support Team
MCR	Mission Control Room
MFCO	Mission Flight Control Officer
MOVE	Mission Operations Voice Enhancement
NESC	NASA Engineering Safety Center
NOTAMS	Notices to Airmen
NOTMARS	Notices to Mariners
PPD	Present Position Display
RAC	Risk Assessment Center
RCC	Range Control Center
RCO	Range Control Officer
RDDS	Range Data Display System
RS	Range Safety
RSO	Range Safety Officer
RTDC	Real-time Data Controller
SC	Surveillance Command
SCO	Surveillance Control Officer

SME	Subject Matter Expert
SMFCO	Senior Mission Flight Control
SO	Surveillance Officer
SSO	System Safety Officer
SSST	Supersonic Sea Skimming Target
TD	Test Director
TDT	Technical Discipline Team
TSO	Telemetry Systems Officer
VAFB	Vandenberg Air Force Base
WFF	Wallops Flight Facility
WSS	Wire Sky Screen

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Appendices

Appendix A1. Preliminary Study Conference Paper: A Cognitive Task Analysis of Safety-Critical Launch Termination Systems

Appendix A2. Preliminary Study Mission Graphics System Requirements

Appendix A3. Preliminary Study Mission Displays Formal Interview Questionnaires

Appendix B. Documents Reviewed

Appendix A1. Preliminary Study Conference Paper: A Cognitive Task Analysis of Safety-Critical Launch Termination Systems

A Cognitive Task Analysis of Safety-Critical Launch Termination Systems

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Abstract. The National Aeronautics and Space Administration (NASA) has been conducting an investigation of human interaction with critical elements of NASA's Launch Termination System (LTS). This safety-critical system requires quick decision making on the part of highly trained users in order to maintain safe launch operations. A team of NASA evaluators has completed a detailed assessment aimed at improving the Graphical User Interface (GUI) of NASA's Range Data Display System (RDDS), a key component of the LTS. The RDDS forms the vital man-machine link which ingests high volumes of system data in real-time and displays this data to NASA's Range Safety personnel to enable them to assess launch vehicle trajectory and performance status. The RDDS displays the real-time state of the launch vehicle and its complex subsystems to users in order to support arm/destruct decisions (made by NASA's Range Safety personnel) to facilitate safe launch operations. These decisions are highly time-sensitive, and users must act quickly in order to prevent serious injury or death and extensive damage to equipment or property.

The NASA assessment team performed a Cognitive Task Analysis (CTA) to derive the user informational requirements needed to develop data driven, user information software requirements in support of a new RDDS software upgrade. The CTA was designed to address the unique aspects of this particular system, while focusing on the operational context within which the system is used by highly specialized personnel. This analysis and the resulting requirements form the first step in providing human factors guidance to software developers throughout the design, development, and fielding of the new RDDS software GUI.

This paper will focus on the applied human factors methods and techniques employed, how these methods and techniques were used to derive user information design requirements, the lessons learned from this activity, and areas for future work. The authors intend to provide human factors practitioners with an example of how CTA methods and techniques may be adapted to meet the particular needs of a project, with special consideration given to the design of safety-critical systems.

Keywords: Cognitive Task Analysis · Launch Operations · Safety-Critical

1 Introduction

A team of evaluators from the NASA Langley Research Center (LaRC) in Hampton, VA provided human factors design guidance for the re-design of a safety-critical system utilized by Range Safety Officers (RSOs) at the Wallops Flight Facility (WFF) on Wallops Island, VA. The RSO's duty is to ensure the safety of the areas in and around the launch pad and along the intended flight path of the launch vehicle before it enters orbit [1]. In order to ensure the safety of these areas, the Range Data Display System (RDDS) is utilized, which forms a safety-critical link between humans and the vehicle during launch operations. The RDDS ingests high volumes of system data in real-time from the launch vehicle and provides graphical and alphanumeric information to RSOs which enables them to assess flight vehicle trajectory and performance status. This visual information is vital in supporting destruct decisions during launch operations.

2 Background

The WFF was established in 1945 by the National Advisory Committee for Aeronautics (NACA, which later became NASA). The WFF is managed by NASA's Goddard Space Flight Center (GSFC) in Greenbelt, MD, and is capable of launching a variety of orbital and sub-orbital vehicles. For the purpose of this assessment, we will focus on those launch vehicles equipped with a Flight Termination System (FTS). The FTS is capable of receiving "arm" and "destruct" commands which are transmitted to the launch vehicle from RSOs located in the Range Safety Control Room. After receiving the "destruct" command, the FTS ignites a shaped explosive charge on board the launch vehicle, triggering an explosion which breaches the fuel tanks, resulting in the destruction of the launch vehicle.

It is the duty of highly trained RSOs located within the Range Safety Control Room to make a destruct decision if the launch vehicle poses any risk to persons or property from liftoff until the vehicle safely reaches orbit. These RSOs rely primarily upon the visual information presented by the RDDS in order to make the decision to initiate a destruct sequence.

The RDDS is comprised of six displays located within the user's primary field of view on the RSO Control Panel. For the purposes of this assessment, the displays were divided into two categories; primary displays and secondary displays. During launch operations, the RSO closely monitors the primary displays for information on vehicle trajectory and performance, while occasionally cross-checking the secondary displays for additional information or to troubleshoot a problem.

Launch vehicle trajectory and performance information is presented in a combination of both alphanumeric readouts and in graphical representations of performance boundaries. Within the RDDS, performance boundaries are depicted on the primary displays and fuse multiple sources of information into a more intuitive graphical depiction to support split-second decision making on the part of the users. These graphical depictions plot the vehicle's current status over a stationary graph of performance boundary lines. The RSO monitors these graphical representations for "parallelism" between the current vehicle status and the boundary lines, as this indicates to the user that there is a problem with the launch.

The secondary displays are used to troubleshoot problems as they arise, or to gain a more detailed understanding of launch vehicle performance. RSOs must interpret information from several disparate sources in order to make the decision to destroy a launch vehicle. In the event that a destruct decision has been made, the RSO sends the arm and destruct commands to the launch vehicle. These commands are initiated by depressing their representative push buttons on the destruct panel located directly in front of the RSO.

3 Method

The assessments team was asked to provide human factors design guidance to support the RDDS re-design effort. This guidance was to be delivered in the form of user information software design requirements to be incorporated into the design of the new RDDS by the software team. After several visits to the WFF to meet with users and observe their interactions with the system, the assessment team determined that a Cognitive Task Analysis (CTA) would yield the best results for requirements generation.

After completing a literature review of CTA methods and techniques [2,3,4], evaluators identified Hoffmann's Protocols for Cognitive Task Analysis [2] as the best fit for the goals and priorities of this assessment.

The assessment team adapted the following elements of Hoffmann's protocols to fit within the planned activities of the RDDS re-design effort; the Documentation Analysis, the Recent Case Walkthrough, the Knowledge Audit, Client Interviews, Career Interviews, Activities Observations, Decision Requirements Analysis, and Action Requirements Analysis (see Fig 1).

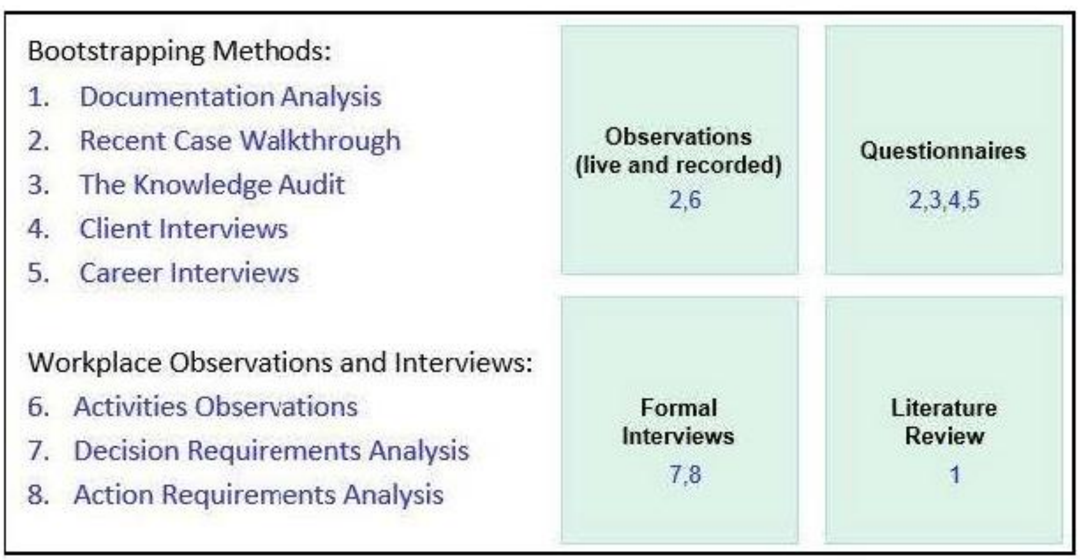

Fig. 1. Adaptation of Hoffman's CTA Protocols to the RDDS re-design effort

The assessment team (in collaboration with WFF representatives) created a plan of execution for this assessment, which conformed to the schedule constraints of the larger system re-design effort. This plan required continuous adaptation over time due to changing resource and personnel limitations. Due to the safety critical nature of the system, the assessment team sought to develop a thorough understanding of the system and the operational context of its use through multiple redundant means of analysis. These included; Subject Matter Expert (SME) interviews, multiple literature reviews, user questionnaires, and formal interviews. Performing a CTA on a safety critical system requires practitioners to develop a full understanding of the user interface to be analyzed before proposing any design changes to user interaction with the system. Even minor changes can result in unintended consequences. Therefore, planned CTA activities should include enough time for practitioners to develop an in-depth understanding the system and how it is used. The plan of execution for this assessment is shown below in Table 1.

Table 1. Plan of execution (activities with the same Order numbers completed in parallel)

Order	Activity	Purpose
1	CTA Methods Lit. Review	Select and adapt CTA methodology
2	SME Interviews	Inform the creation of activities and supporting materials
2	RDDS Ops. Lit. Review	Inform the creation of activities and supporting materials
2	Analogous Sys. Lit Review	Inform the creation of activities and supporting materials
3	Observations (live and recorded)	Inform the creation of activities and supporting materials, Elements 2 & 6 (see Fig. 1)
4	Questionnaire #1	Data collection - Elements 2, 3, 4, 5 (see Fig. 1) and System Usability Survey (SUS)
5	Formal Interviews	Data collection - Decision and Action Requirements Analyses
6	Questionnaire #2	Data collection - Elements 2, 3, 4, 5 (see Fig. 1) and System Satisfaction Survey
7	Analysis of collected data	Statistical analysis of questionnaire/survey results
7	Phase diagram generation	Map decision and action requirements to derive basic informational requirements
8	User information Requirements Synthesis	Incorporate data from all activities, identify trends, and generate user information requirements

An initial interview with a Subject Matter Expert (SME) familiar with RSO duties and the RDDS was conducted, and this information was later used to inform the creation of activities and supporting materials designed to incorporate various elements of Hoffman's CTA protocols.

Observations of users interacting with the RDDS (both live and recorded) provided evaluators with insight into the operational context of the system's use. The RDDS is capable of re-playing the data recorded from previous launches as well as simulating custom-designed launches for training purposes. This capability proved useful in completing both the Recent Case Walkthrough and the Activities Observations elements.

Two additional literature reviews were completed to inform the creation of the user questionnaires and interviews. A literature review was conducted of NASA documentation detailing system functionality, Range Safety operations, RSO training materials, WFF general launch operations, and human systems integration [5,6,7,8,9]. Another litereature review examined analogous systems, both within and outside of NASA [10,11,12,13]. The three literature reviews completed for this assessment (CTA methodology, RDDS operations, and analogous systems) fulfilled the Documentation Analysis element.

Two questionnaires were developed and administered to users, one before formal interviews and another afterwards. These questionnaires were designed to elicit detailed user data through combining several elements of Hoffman's protocols. The first questionnaire also included a System Usability Survey (SUS) [14], which was used to evaluate the RDDS and identify potential deficiencies in the system. Following the formal interview, the second questionnaire was administered, which contained a System Satisfaction Survey. This survey was made up of corresponding adjective ratings [15] used to confirm the SUS results collected in the first questionnaire. Once working prototypes of the new RDDS are operational, these surveys can be administered once more to measure the effectiveness of incorporating usability improvements into the new system.

Formal interviews were conducted with each user of the RDDS, and the questions were designed to elicit the decision requirements and action requirements RSOs rely upon to make destruct decisions. The data collected from these interviews formed the basis of phase diagrams for each set of decision and action requirements. These diagrams were used to visualize the informational requirements of the system to aid in user information requirements synthesis.

4 Discussion

While the results of this assessment were specifically targeted for NASA use, what follows is a high-level overview of how the collected data formed the basis of the user information requirements delivered in support of the RDDS re-design effort.

Statistical analyses of user questionnaires revealed commonality in the perceived strengths and weaknesses of the current system across all areas numerically rated by users. User comments and responses to open-ended questions revealed a number of common themes relating to areas in need of improvement. As common themes began to emerge, these responses were separated into "bins" of similar feedback during the analysis process. The adjective ratings of the System Satisfaction Survey were highly correlated to the SUS results.

The data collected through formal interviews with RDDS users were later analyzed to create phase diagrams to map out a series of decision requirements ranging from monitoring parameter exceedances (see Fig. 2) to cases unique only to WFF range operations. A phase diagram was also created for the destruction of a launch vehicle.

These phase diagrams provided the assessment team with insight into the unique information requirements that users rely upon to make difficult decisions and effectively take action. Understanding the information required by users in order to effectively interact with the system was very helpful in generating the user information requirements necessary to support the re-design effort.

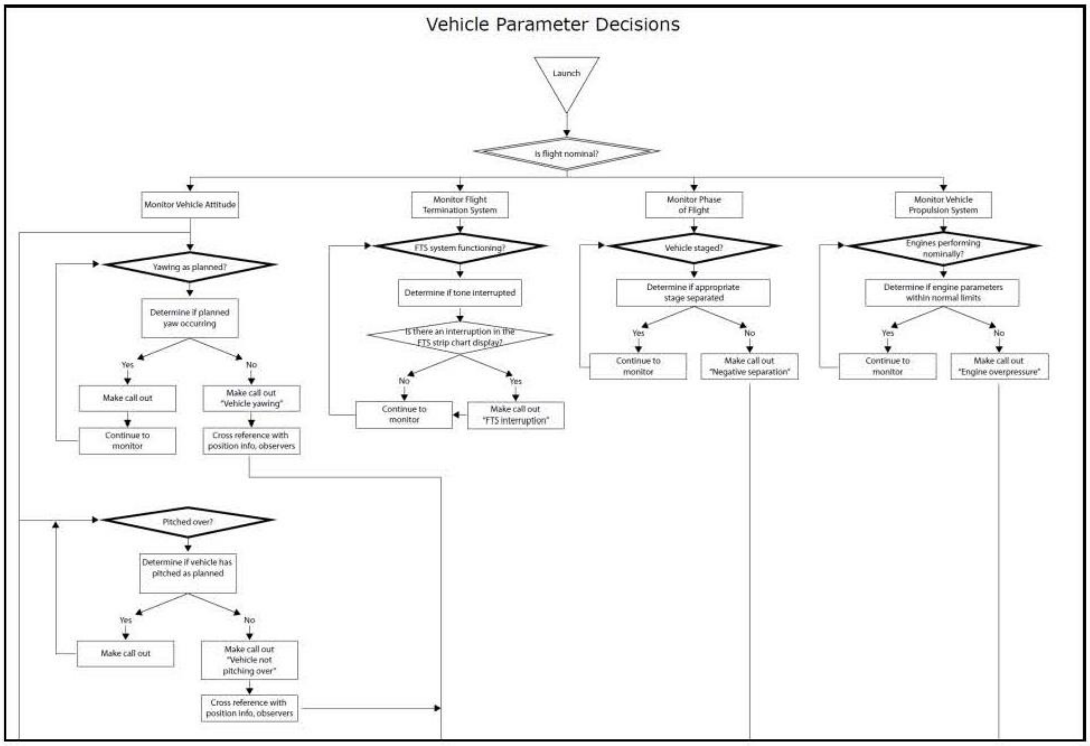

Fig. 2. Phase Diagram for Vehicle Parameter Decision Requirements

Evaluators observed user interactions with the RDDS on several occasions, employing heuristic evaluation methods to analyze the usability of the current system. These observations identified a number of areas within the system which evaluators were able to explore in more detail in the knowledge elicitation activities which followed later.

The assessment team met frequently throughout the data analysis process to discuss the preliminary results and emerging trends in the data. Upon completion of the data analysis phase, the assessment team held a series of requirements generation meetings in which common themes and issues were rank ordered by priority to develop draft requirements.

The informational requirements identified in the phase diagrams required the least interpretation on the part of the assessment team. As such, these could be easily incorporated into the final user information software requirements document.

Some areas for improvement within the system were only apparent to the assessment team, due to their professional training in human factors and experience in evaluating similar systems. The assessment team discussed each of these cases after all other data was collected and analyzed. After reaching a consensus, the assessment team generated new user requirements to address the issue.

All draft requirements were discussed and reviewed in detail by the assessment team prior to delivery. The final software requirements document was well received by the RDDS software development team, who were heavily involved throughout the CTA process.

5 Conclusion

This assessment represents the first in a series of activities intended to provide human factors design guidance in support of the RDDS re-design effort. The CTA methods and techniques employed provided evaluators with valuable insight into the interactions between users and the system, while at the same time building a detailed knowledge base from which to draw throughout future design activities.

Among the many lessons learned from this assessment, the assessment team found it informative to witness the tremendous insight that CTA techniques can provide when applied to highly trained users interacting with complex, safety-critical systems. The benefits of performing a CTA are multiplied when practitioners collaborate with a team of proactive and engaged developers (like the RDDS software team), interested in creating the best possible user interface.

Many of the CTA activities outlined here are very time consuming to plan and execute. This can be true for both the practitioners and the users, so it is necessary to provide sufficient time in between activities to ensure proper execution.

Areas for future work with the RDDS re-design effort include; detailed design activities with users, storyboarding and development of a prototype system, and user testing/evaluation of the prototype system as part of an iterative design cycle. As with any safety-critical system, extensive validation and verification of the new system will be necessary before it enters into service.

The applied human factors methods and techniques described herein are intended to provide an example of how NASA evaluators adapted a CTA methodology to meet the particular needs of this assessment.

Acknowledgements. The assessment team would like to thank the WFF RDDS Software and Range Safety organizations for their time, assistance, and support in the completion of this effort. The assessment team would also like to thank the NASA Engineering and Safety Center (NESC) for funding this assessment to apply human factors techniques to this safety critical component of the Wallops Flight Facility Launch Termination System.

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Appendix A2. Preliminary Study Mission Graphics System Requirements

System Requirements			
ID#	**Requirement**	**Rationale**	**Notes**
1	The live video feed of the launch pad shall be within the user's primary field of view	Formal interviews	Users reference the live video feed when conflicting or confusing information is displayed on the VSD
2	The system shall have the ability to revert to "classic" mode (the current design) for users who would prefer to use the previously certified system.	From Questionnaires, Observations	Some users expressed discomfort at the idea of "changing too much" of the system all at once. Having a "classic" mode would allow users time to transition to the new system. This capability may also prove to be a useful tool for the purpose of training users on the new system.
3	The display shall consist of two types of elements: 1) Required elements, which are always displayed 2) Optional elements , the display of which can be toggled on/off by the user	Formal interviews, questionnaire results	This requirement ensures that users cannot configure the display in an unsafe way (e.g. missing information needed to perform their tasks).
4	For all display elements not expressly listed, all other required and optional elements shall be defined and categorized collaboratively by users and the mission displays software team.		This ensures users are involved in determining which items are required elements and which items are optional.
5	The display shall incorporate a hierarchy which prioritizes which display elements to display or automatically de-clutter in case of a conflict between on-screen objects.		This requirement is intended to reduce display clutter, which will be necessary with user selectable/optional display elements.
6	All symbols shall be depicted uniquely, in a manner easily differentiable from other display elements.		

7	The system shall indicate vehicle parameters graphically when applicable	Formal interviews	Users indicated that a simple readout of engine parameters is not the ideal way of displaying this information. Graphical information can increase processing times.
8	The VSD shall display the nominal vehicle pitchover	Formal interviews	Users indicated that it can be difficult to determine when the vehicle is pitching over
9	The geography depicted within the system shall accurately reflect modern day geography of areas surrounding the launch facility and islands along the path of vehicle travel		
10	The ability for users to manually override the pan function shall be applied to the PPD	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that the system does not have the capability to "pan," which hinders their situational awareness
11	Users shall be able to override default screen changes through input devices		
12	An indication shall be provided at any time in which the system is delayed due to processing or other constraints		Similar to the hourglass symbol in Windows, this provides user with necessary feedback
13	The system shall provide feedback that it has received a command from the user (e.g. selections, control inputs, etc.)		Providing feedback to the user after an input has been received improves the overall usability of the system
14	All relevant times shall be optionally displayed (at the users discretion) on every display.	From Questionnaires, Observations	Users engage in time critical activities and would benefit from ready access to time information
15	Wherever possible, all relevant information related to time shall be contained within the same small area (or window) within the display.	From Questionnaires, Observations	Locating time information together will ease user interpretation of time values
16	The time window shall have a default location upon system initiation.	From Questionnaires, Observations	

17	The default location for relevant times shall not obscure important information on the display.	From Questionnaires, Observations	
18	The user shall have the ability to control where the time window appears on each display via multiple methods (i.e. keyboard, mouse, joystick, etc.)	From Questionnaires, Observations	Depending on job duties or personal preference, users may feel the need to relocate the time display to a position on-screen which is more easily viewed.
19	Time representation shall be clearly perceptible to all users from their normal seated positions	Formal interviews, applicable standards, etc.	
20	Green Time shall be depicted	Formal interviews, applicable standards, etc.	
21	Green Time shall automatically start counting down as soon as a loss of data occurs	Formal interviews, applicable standards, etc.	
22	Green Time shall indicate to the user when the appropriate time has been reached for a destruct action	Formal interviews, applicable standards, etc.	
23	In the event that data is restored, Green Time shall stop and indicate to the user that data has been restored	Formal interviews, applicable standards, etc.	
24	Menu navigation within the system shall be intuitive to the user, requiring little or no user memorization to operate.	From Questionnaires, Observations	Some users felt the current system for switching between displays requires too much memorization.
25	Controls for menu navigation within the system shall be designed to allow for quick navigation.	From Questionnaires, Observations	
26	Controls for menu navigation shall be consistent with menu controls utilized in modern consumer electronics.	From Questionnaires, Observations	Some users described the current system's controls as "archaic", but adopting menu navigation controls from consumer electronics should address this issue.

27	The user shall have the ability to navigate menus via multiple methods of control (i.e. keyboard, mouse, joystick, dedicated buttons, etc.)	From Questionnaires, Observations	It is important to provide redundant means of menu navigation control in the event of equipment failure.
28	Alerting mechanisms shall be incorporated into the system utilizing industry alerting standards (aural, visual, etc.)	From Questionnaires, Observations	Providing users with effective alerts will improve their abilities to execute necessary tasks
29	Users shall be able to disable alerting mechanisms at their discretion.	From Questionnaires, Observations	
30	Alerting mechanisms shall be implemented to aid in user identification of critical events.	From Questionnaires, Observations	
31	Alerting mechanisms shall be implemented in ways which do not constitute a nuisance to users.	From Questionnaires, Observations	
32	Any audible alerts shall not interfere with crew voice communications	Formal interviews	Users stated their concern that using auditory alerts would interfere with their communications and stated their preference for visual alerts
33	Alerts shall be implemented to indicate off-nominal behavior	Formal interviews, applicable standards, etc.	
34	A change in system state shall not be indicated by a color change alone	Formal interviews, applicable standards	Users indicated that events (e.g. staging) are indicated only by a change in color. Recommend using a simple LED-type, on/off indication for system state.
35	Initial data entry and setup of the system shall be intuitive to the user.	From Questionnaires, Observations	
36	Initial data entry and setup of the system shall be achieved via user friendly methods already established in consumer electronics.	From Questionnaires, Observations	
37	Label text color shall be consistent throughout the system	Applicable standards	
38	Readout text font shall be consistent throughout the system	Applicable standards	

39	System readout text and system label text shall be differentiable by users	Applicable standards	
40	Readout text shall be limited to an appropriate number of significant digits	Applicable standards	
41	All text shall be arrayed horizontally for legibility.		
42	On a case by case basis (due to space constraints), text shall be arranged vertically such that complete words or phrases shall be rotated counterclockwise 90 degrees vertically to maintain left-to-right legibility.	Formal interviews, questionnaire results	This requirement prevents vertically arrayed words in which one letter is "stacked" on top of the other, and instead requires that complete words or phrases be rotated as a piece to maintain left-to-right legibility.
43	Data Source symbols shall be consistent across displays	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that the current system portrays data sources in a hindering manner, which impacts their ability to completing tasks
44	Color usage for Data Source symbols shall be consistent in meaning	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that the color usage of the data sources are NOT easily understood
45	An indication shall be provided prior to any automatic display changes by the system	Formal interviews, applicable standards, etc.	
46	If necessary, screen changes shall be conducted by default automatically by the system at a given specified point/stage in the launch	Formal interviews, applicable standards, etc.	
47	Colors shall be clearly differentiable from each other from the user's seated position	Observations, Standards	This is intended to reduce the potential for user confusion due to colors which are difficult to distinguish
48	Use of color shall be consistent with consumer color usage standards and conventions (e.g. "Green = Go or Good", "Red = Stop or Bad", etc.)	Observations, Standards	This is intended to reduce the potential for user confusion
49	The philosophy behind color usage shall be described in detail in the design guide	Observations	The documentation of the chosen color philosophy will provide a resource for continued use by the users

50	Any color changes shall be updated in the design guide	Observations	This keeps meanings consistent and reduces the potential for confusion as new colors or features are added
51	All colors utilized in the display shall be consistent with system-wide color standards.		This ensures consistency of color philosophy used throughout the system, a must for any user-centered system.

Instantaneous Impact Prediction Display (IIP)			
ID#	**Requirement**	**Rationale**	**Notes**
1	All text shown on the mission graphics displays shall be clearly legible to all users from their normal seated positions.	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that much of the smaller text can only be read by standing up and looking closely at the screen, some questioned why it is even shown if it cannot be read?
2	All text shall be arrayed horizontally for legibility.		
3	On a case by case basis (due to space constraints), text shall be arranged vertically such that complete words or phrases shall be rotated counterclockwise 90 degrees vertically to maintain left-to-right legibility.	Formal interviews, questionnaire results	This requirement prevents vertically arrayed words in which one letter is "stacked" on top of the other, and instead requires that complete words or phrases be rotated as a piece to maintain left-to-right legibility.
4	Numerical values with decimal places shall display the minimum numerical length necessary for the user (as determined by the users in collaboration with the software team).		This requirement prevents the display of unnecessary digits, which can induce artificial delays on user comprehension.
5	All colors utilized in the display shall be consistent with system-wide color standards.		This ensures consistency of color philosophy used throughout the system, a must for any user-centered system.
6	The display shall consist of two types of elements: 1) Required elements, which are always displayed 2) Optional elements , the display of which can be toggled on/off by the user	Formal interviews, questionnaire results	This requirement ensures that users cannot configure the display in an unsafe way (e.g. missing information needed to perform their tasks).

7	For all display elements not expressly listed, all other required and optional elements shall be defined and categorized collaboratively by users and the mission displays software team.		This ensures users are involved in determining which items are required elements and which items are optional.
8	The display shall incorporate a hierarchy which prioritizes which display elements to display or automatically de-clutter in case of a conflict between on-screen objects.		This requirement is intended to reduce display clutter, which will be necessary with user selectable/optional display elements.
9	All geographical features depicted on the mission graphics displays shall be accurately depicted to within 1 mile for 100 mi. launch site radius and 5 miles all other areas.	Formal interviews, questionnaire results	Questionnaire results indicated that most users doubt the accuracy of the current system's geographical depictions.
10	Population centers shall be depicted as an optional display element.	Formal interviews, questionnaire results	As requested by users.
11	A population density overlay shall be depicted as an optional display element.	Formal interviews, questionnaire results	Highly populated areas may exist outside of major cities, and a population density overlay is able to convey that information quickly to a user grappling with a destruct decision.
12	Geo-political boundaries shall be depicted as an optional feature..	Formal interviews, questionnaire results	As requested by users.
13	Geo-political features shall be labeled as an optional feature.	Formal interviews, questionnaire results	As requested by users.
14	Land masses shall be depicted in a way that is clearly differentiable from bodies of water.	Formal interviews, questionnaire results	As requested by users.
15	Bodies of water shall be depicted in a way that is clearly differentiable from land masses.	Formal interviews, questionnaire results	As requested by users.
16	Boundary lines shall be depicted in a way that is clearly differentiable from other lines displayed simultaneously on screen.		This reduces the potential for confusion with other lines displayed.

17	The system shall be aware of boundary violations and will provide some indication to the user that a boundary violation has occurred.	Observations	This reduces the reliance on humans to detect finite criteria already known to the system.
18	Nominal path lines shall be depicted in a way that is clearly differentiable from other lines displayed simultaneously on screen.		This reduces the potential for confusion with other lines displayed.
19	All symbols shall be depicted uniquely, in a manner easily differentiable from other display elements.		This reduces the potential for confusion with other symbols displayed.
20	By default, the vehicle symbol shall always be displayed on screen.		The location of the vehicle is critical to successful task completion. The user may decide to manually shift the focus off of the vehicle, but by default it should be centered.
21	The system shall be aware of vehicle phase of flight changes (e.g. stage separations, perigee gates, etc.) and will provide some indication to the user that a vehicle phase of flight change has occurred.	Questionnaires, Formal interviews	If the system is aware of phase of flight changes and provides this information to the user it will increase user situational awareness.
22	The display shall support optional pan/zoom/scaling which is controllable by the user.	Questionnaires, Formal interviews	Users indicated that having the option to control pan/zoom/scaling would be beneficial.
23	The display shall allow an optional automatic pan/zoom/scaling setting which keeps the aircraft symbol centered at all times on the display.	Questionnaires, Formal interviews	Some users indicated that they do not want the new system to feature only manual control of pan/zoom/scaling, so the option should exist for automatic behaviors
24	The transition from automatic pan/zoom/scaling to manual control shall occur quickly and with minimal user input to facilitate emergency use.	Observations	The time critical nature of user's tasks necessitates a quick transition between automatic and manual modes. An example of this would be default automated behaviors occurring until joystick input is detected, at which point manual control mode is activated.

25	An indication of range (i.e. range scale, range ring, etc.) for a given level of zoom/scaling shall be provided as a point of reference for the user.	Observations, formal interviews	Some users identified that map ranges are unknown. There are a number of methods used in other safety critical systems to depict range in an unobtrusive way, and these aides improve user's situational awareness.
26	The display shall provide the user with an indication of the location of the vehicle symbol or other important symbols relative to the area currently being displayed (e.g. mini map w/ focus window or other indicator).	Observations	In systems with manual control, the potential exists for users to change viewable area such that critical information (like the vehicle symbol) is no longer displayed.
27	The overall launch time shall be displayed.	Observations, formal interviews	
28	The system shall provide the optional ability for the user to mark time (via a virtual stopwatch or some other means).	Observations	Timing appears to be a critical element for user task completion, so it is important that operators be provided with any tools in the system which they may find beneficial
29	The system shall be aware of green time and shall provide some indication to the user that green time is in effect.	Formal interviews, Questionnaires, Observations	Accurate green time is vital for user task completion, and the system can more accurately record this parameter instead of relying on users.
30	A green time countdown timer shall be displayed to the user.	Formal interviews, Questionnaires	Users indicated that having a green time value displayed would aid them in task completion
31	The green time countdown timer shall provide an indication to the user that green time is about to be exceeded.	Formal interviews, Observations	It's important for users to know that green time is about to be exceeded, and a notification would increase user situational awareness.
32	The green time countdown timer shall provide a unique indication to the user that green time has expired.	Observations	It's important for users to know that green time has been exceeded, and a notification would increase user situational awareness.
33	The geography depicted on the IIP display shall accurately reflect modern geography of areas surrounding the launch facility and islands along the path of vehicle travel	Formal interviews	Users stated that more accurate geographical information would aid in their decision-making.

34	A depiction of debris prediction shall be incorporated in the IIP display	Formal interviews	Users indicated that debris field information overlaid on the IIP display would aid in their decision-making
35	A time value shall be associated with the depiction of the debris predication so as to display predicted debris within a certain time range	Formal interviews, Observations	A time value would aid users in their decision-making.
36	The system shall indicate where the transmitter horizon is	Formal interviews	Users use sticky notes to remember when the vehicle will fall below the FTS transmitter horizon
37	Hands-off areas shall be depicted in a perceptible manner to all users	Formal interviews	Users indicated that hands-off areas are sometimes not perceptible and need to user their judgment in knowing when to be hands-off
38	Hands-off areas shall be depicted in a manner that is legible to all users from a seated position	Formal interviews	Lines depicting hands-off areas should be visually legible to all users from a comfortable seated position (i.e. users should not have to lean forward to see the depiction)
39	If useful to the user, a countdown time value shall be depicted for areas designated as hands-off (i.e. depicting how much time is left for remaining hands-off)	Observations	Having a countdown value depicting how much longer the user should remain hands-off in designated areas could aid in their judgment and understand how much time is remaining over a specific area in the even that a destruct action needs to be taken

Primary Position Display (PPD)			
ID#	**Requirement**	**Rationale**	**Notes**
1	All text shown on the PPD shall be clearly legible to all users from their normal seated positions	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that much of the smaller text can only be read by standing up and looking closely at the screen, some questioned why it is even shown if it cannot be read?
2	All color shown on the PPD shall be consistent in meaning on the PPD itself and across all displays	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that current colors presented on the displays do not provide any useful information and lack meaning. There is too much inconsistency in the colors between displays and within the same display.

3	The ability for users to manually override the zoom in and out function of maps and charts shall be applied to the PPD	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that the system does not have the capability to "zoom," which hinders their situational awareness
4	The ability for users to manually override the pan function shall be applied to the PPD	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that the system does not have the capability to "pan," which hinders their situational awareness
5	Data Source symbols shall be consistent across displays	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that the current system portrays data sources in a hindering manner, which impacts their ability to completing tasks
6	Color usage for Data Source symbols shall be consistent in meaning	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that the color usage of the data sources are NOT easily understood
7	Color usage of termination boundaries shall be consistent in meaning across all displays	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that the color usage of termination boundaries were not consistent in meaning to other depicted lines in the system
8	Time shall be displayed on the PPD	Formal interviews, applicable standards, etc.	In formal interviews and questionnaires, users mentioned that time was not displayed on the PPD and only appeared on one display. They said they would prefer having it on all screens, including the PPD
9	Time shall be clearly legible to all users from their normal seated positions	Formal interviews, applicable standards, etc.	In formal interviews and questionnaires, users mentioned that time was not displayed on the PPD and only appeared on one display. They said they would prefer having it on all screens, including the PPD
10	The velocity vs time depiction shall include a path depicting the history of the vehicle	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that they would prefer a depiction of the vehicle's history to aid in their situation awareness
11	Vehicle battery percentage shall be depicted on the PPD	Formal interviews, applicable standards, etc.	Users indicated that they would prefer knowing the battery percentage on all displays for situation awareness
12	Battery percentage shall be clearly legible to all users from their normal seated position	Formal interviews, applicable standards, etc.	Battery percentage should be legible to all users so as to not cause eye strain or second-guessing as to the value for proper judgment

13	Battery percentage color usage shall be consistent in meaning across all displays	Formal interviews, applicable standards, etc.	Color usage needs to be consistent throughout the system with each color representing something specific (no one color shall be used for multiple meanings).
14	An indication shall be provided prior to any automatic display changes by the system	Formal interviews, applicable standards, etc.	Users indicated preference for having the system automatically (with the option to override the system) switch displays depending on the phase of flight. Currently users have to manually switch displays by overreaching to a near-by keyboard - this is unsuitable since it takes more time away from the user and depends on their ability to switch screens without looking at the keyboard so as to not remove their focus off of the displays. However, the user should be notified before any display change occurs (to give the option of overriding the system)
15	Screen changes shall be conducted by default automatically by the system at a given specified point/stage in the launch	Formal interviews, applicable standards, etc.	Users indicated preference for having the system automatically (with the option to override the system) switch displays depending on the phase of flight. Currently users have to manually switch displays by overreaching to a near-by keyboard - this is unsuitable since it takes more time away from the user and depends on their ability to switch screens without looking at the keyboard so as to not remove their focus off of the displays. However, the user should be notified before any display change occurs (to give the option of overriding the system)
16	The launch vehicle symbol shall be centered on the PPD at all times	Formal interviews, applicable standards, etc.	Users indicated that the launch vehicle symbol is not centered and moves along the screen (and when it reaches the end of the screen, the display abruptly changes). Users mentioned preference for having the vehicle centered on the screen at all times.
18	"Pan" and "zoom" functions shall, by default, be automatically conducted by system	Formal interviews, applicable standards, etc.	Users indicated that having automatic pan and zoom functions would aid in their workload and situation awareness
19	The velocity vs time depiction shall be depicted on its own separate graph	Formal interviews, applicable standards, etc.	Users commented that they did not prefer to having the "velocity vs time" graph overlaid on top of the other graph on the PPD.
20	Green Time shall be depicted on the PPD	Formal interviews, applicable standards, etc.	Users indicated having Green Time on the display would aid in their situation awareness and would aid in their situation awareness, which has an impact on safety

21	Green Time shall, by default, automatically start counting down as soon as a loss of data occurs	Formal interviews, applicable standards, etc.	Users indicated that there is no indication of when Green Time should start and most is based on judgment or when loss of telemetry data is realized (which is not perceptible to the user)
22	An indication shall be provided to the user when the appropriate Green Time has been reached for a destruct action	Formal interviews, applicable standards, etc.	Users indicated that there is a specific Green Time associated with taking a destruct action - the system should aid the user so there is no second-guessing whether a vehicle should be destroyed
23	In the event that data is restored, Green Time shall stop and indicate to the user that data has been restored	Formal interviews, applicable standards, etc.	Users indicated that there is nothing to alert them when data is restored and should stop counting Green Time. This is because they use off-screen aid to count so when data is restored, their attention may be on the time clock or the paper aid they have set in place.
24	Destruct lines color usage shall be consistent throughout the entire system	Formal interviews, applicable standards, etc.	Color usage needs to be consistent throughout the system with each color representing something specific (no one color shall be used for multiple meanings). User indicated that the color of destruct lines are not very distinguishable from other colors in the system used for other meanings
25	An indication of pitch over, or the vehicle going "over the shoulder" shall be clearly depicted	Formal interviews, applicable standards, etc.	Users indicated that they would prefer having an indication of when the vehicle is going "over the shoulder," which would aid in their situation awareness and aid in their judgment of taking a destruct action
26	The nominal path of the vehicle shall be depicted in a specified color that is consistent throughout the system	Formal interviews, applicable standards, etc.	Color usage needs to be consistent throughout the system with each color representing something specific (no one color shall be used for multiple meanings). User indicated that the color of nominal path is not very distinguishable from other colors in the system used for other meanings
27	A visual alert shall be implemented to indicate off-nominal behavior that is perceptible to the user	Formal interviews, applicable standards, etc.	Users commented saying that the current visuals (colors changing) do not capture their attention to when off-nominal behaviors are occurring during a launch
28	Geographical areas surrounding the launch facility shall be depicted on the PPD	Formal interviews, applicable standards, etc.	Users commented that geography is not presented on the PPD and would be helpful to have a depiction of areas surrounding the launch facility

29	The geography depicted on the PPD shall accurately reflect modern day geography of areas surrounding the launch facility	Formal interviews, applicable standards, etc.	Users commented that geography currently present in the system is not up to date and does not reflect modern day geography, which impacts true hands-off time and understanding debris prediction if a destruct action is necessary
30	Debris prediction shall be displayed on the PPD display	Formal interviews, applicable standards, etc.	Users commented that understanding where the debris would land would be helpful to know what sort of impact it would make if a destruct action was necessary
31	If useful to the user, a time value shall be associated with the depiction of the debris predication so as to display predicted debris within a certain time range	Formal interviews, applicable standards, etc.	Having a time depiction associated with the debris prediction would improve situation awareness and would allow for more accurate decision-making if a destruct action was necessary (e.g. if a destruct action needs to be taken, then within 30 seconds the debris will cause this much damage in a particular area)
32	The display shall allow an optional automatic pan/zoom/scaling setting which keeps the launch vehicle symbol centered at all times on the display	Formal interviews, applicable standards, etc.	In formal interviews, users mentioned that the system does not keep the vehicle symbol centered on the display and is always a certain size - they would prefer to be able to change pan/zoom/scaling settings to better view the vehicle while on its path

Flight Termination System (FTS) & Vehicle Situation Display (VSD)				
ID#	**Requirement**	**Rationale**	**Notes**	**Display**
1	The live video feed of the launch pad shall be within the user's primary field of view	Formal interviews	Users reference the live video feed when conflicting or confusing information is displayed on the VSD	VSD
2	Vehicle specific nominal parameters shall be displayed to the user graphically	Formal interviews	Users indicated that determining when the vehicle is in range or out of range was a matter of judgment	VSD
3	Vehicle specific nominal parameters shall be displayed to the user alphanumerically	Formal interviews		VSD
4	Nominal vehicle engine chamber pressure shall be displayed	Formal interviews		VSD
5	Nominal vehicle pitchover for a given	Formal interviews		VSD

	flight profile shall be displayed			
6	Nominal vehicle yaw for a given flight profile shall be displayed	Formal interviews		VSD
7	The system shall provide an indication to the user when vehicle specific parameters are in an off nominal state graphically	Formal interviews	Users indicated that being "cued" into an off nominal parameter would be useful to avoid missing an off nominal event	VSD
8	The system shall indicate when the vehicle engine chamber pressure is in an off nominal state	Formal interviews		VSD
9	The system shall indicate when the nominal vehicle pitch is in an off nominal state	Formal interviews		VSD
10	The system shall indicate when the nominal vehicle yaw is in an off nominal state	Formal interviews		VSD
11	Times of planned staging events shall be displayed to the user in time after liftoff	Formal interviews		VSD
12	The system shall provide an indication to the user when staging events happen	Formal interviews		VSD
13	FTS 1 tone dropouts shall be perceptible to the user during launch operations	Formal interviews, applicable standards	Users indicated that it is difficult to determine when tone has dropped from the FTS and there were cases when users missed calling out tone dropout	FTS
14	FTS 2 tone dropouts shall be perceptible to the user during launch operations			
15	Each individual FTS system status feedback indication shall be perceptible from each other to the user at all times	Formal interviews, applicable standards	Users indicated that it can be difficult to determine which FTS system has experienced a dropout because both are displayed on the same strip chart in the same color	FTS

16	The system shall provide sufficient enough information to allow the user to determine when the vehicle is tumbling	Formal interviews	Users indicated that mission rules are written to terminate the flight in the event of a tumbling vehicle. Users use the pitch/roll/yaw display to determine when a vehicle is tumbling	VSD
17	The FTS display shall display FTS voltage history before launch	Formal interviews	Users indicated that voltage is important in determining when to change transmitters on the FTS, but voltage would not be used during flight to make decisions	FTS
18	Each individual FTS voltage indications shall be perceptible from each other to the user at all times	Formal Interviews		FTS
19	The system shall indicate vehicle parameters graphically when applicable	Formal interviews	Users indicated that a simple readout of engine parameters is not the ideal way of displaying this information. Graphical information can increase processing times.	VSD
20	The VSD shall display the planned nominal vehicle state for a wind corrected trajectory	Formal interviews	Wind corrected trajectories can resemble an errant vehicle heading towards land during early stages of a launch. Users would like to have an idea of what the vehicle is expected to do	VSD
21	Nominal FTS 1 values shall be displayed to the user	Formal interviews	Users indicated that it is difficult to know when the FTS system is in an off nominal state without training	FTS
22	Nominal FTS 2 values shall be displayed to the user			
23	The system shall indicate to the user when FTS parameters are in an off nominal state	Formal interviews		FTS
24	Any audible alerts shall not interfere with crew voice communications	Formal interviews	Users stated their concern that using auditory alerts would interfere with their communications and stated their preference for visual alerts	VSD/FTS
25	T-time shall be displayed to the user at all times	Formal interviews	Users indicated that looking up to see the launch clock was distracting and undesirable	VSD
26	T-time shall be displayed to the user at all times	Formal interviews	Users indicated that looking up to see the launch clock was distracting and undesirable	FTS

27	The system shall display the nominal vehicle pitchover for each launch	Formal interviews	Users indicated that it can be difficult to determine when the vehicle is pitching over	VSD
28	The system shall allow flight profiles to be uploaded			VSD

Appendix A3. Preliminary Study Mission Displays Formal Interview Questionnaires

Decision Requirements: Vehicle Parameters

Interviewer:	Decision Designation What are the decisions made for vehicle parameters?
Participant:	
Date:	
Start Time:	
End Time:	

1.0 **What is the overall goal of the decision?**

1.1 Why does this decision have to be made?

1.2 At what point in a launch is this decision made?

2.0 **How is the decision made? What are the informational cues?**

2.1 What information is needed?

2.2 Where is the information located?

2.3 How is this information depicted?

2.5 What do you do before the launch to prepare for the decision?

2.5 Do you reference any information sources outside the workstation?

2.6 How can you predict it will go outside the boundaries?

2.7 Is the information easy to comprehend? Why or why not?

2.8 When is the information difficult to comprehend? Why?

3.0 **In what ways can the decision be difficult? Have there been cases where you were "on the fence"?**

3.1 If so, then what did it look like?

4.0 **How do you maintain situational awareness between all information sources when making this decision?**

4.1 What information do all safety officers use in their roles?

5.0 **How much time or effort is involved in making this decision?**

5.1 Are there minimum reaction times?

5.2 If so, then is it easy to meet the minimum reaction times?

6.0 **How do users compensate for deficiencies in the system? (memory aids, reminders, work-arounds)**

6.1 What are the procedures built around deficiencies?

6.2 What information do you need to have with you that is not provided by the system?

6.3 Do you have to memorize anything?

7.0 **What display features may cause human errors and what are the consequences of those errors?**

7.1 What are the consequences associated with these errors?

8.0 **What kinds of additional aids might be useful? (For instance, predictive aids, alerts, warnings, automated function.)**

8.1 How do you mentally envision the vehicle state? Is it different from what is depicted?

Decision Requirements: Performance Boundary Violations

Interviewer	Decision Designation What are the decisions made to determine performance boundary violations?
Participant:	
Date:	
Start Time:	
End Time:	

1.0 **What is the overall goal of the decision?**

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1.1 Why does this decision have to be made?

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1.2 At what point in a launch is this decision made?

____

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2.0 **How is the decision made? What are the informational cues?**

____

____

2.1 What information is needed?

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____

2.2 Where is the information located?

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2.3 How is this information depicted?

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2.5 What do you do before the launch to prepare for the decision?

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____

2.5 Do you reference any information sources outside the workstation?

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____

2.6 How can you predict it will go outside the boundaries?

2.7 Is the information easy to comprehend? Why or why not?

2.8 When is the information difficult to comprehend? Why?

3.0 **In what ways can the decision be difficult? Have there been cases where you were "on the fence"?**

3.1 If so, then what did it look like?

4.0 **How do you maintain situational awareness between all information sources when making this decision?**

4.1 What information do all safety officers use in their roles?

5.0 **How much time or effort is involved in making this decision?**

5.1 Are there minimum reaction times?

5.2 If so, then is it easy to meet the minimum reaction times?

6.0 **Are there any local work-arounds to compensate for workplace or technology deficiencies?**

6.1 What are the procedures built around deficiencies?

6.2 What information do you need to have with you that is not provided by the system?

6.3 Do you have to memorize anything?

7.0 **What display features may cause human errors and what are the consequences of those errors?**

7.1 What are the consequences associated with these errors?

8.0 **What kinds of additional aids might be useful? (For instance, predictive aids, alerts, warnings, automated function.)**

8.1 How do you mentally envision the vehicle state? Is it different from what is depicted?

Decision Requirements: Hands-off Time

Interviewer:	Decision Designation What are the decisions made for determining Hand-off Time?
Participant:	
Date:	
Start Time:	
End Time:	

1.0 **What is the overall goal of the decision?**

1.1 Why does this decision have to be made?

1.2 At what point in a launch is this decision made?

2.0 **How is the decision made? What are the informational cues?**

2.1 What information is needed?

2.2 Where is the information located?

2.3 How is this information depicted?

2.5 What do you do before the launch to prepare for the decision?

2.5 Do you reference any information sources outside the workstation?

2.6 How can you predict it will go outside the boundaries?

2.7 Is the information easy to comprehend? Why or why not?

2.8 When is the information difficult to comprehend? Why?

3.0 **In what ways can the decision be difficult? Have there been cases where you were "on the fence"?**

3.1 If so, then what did it look like?

4.0 **How do you maintain situational awareness between all information sources when making this decision?**

4.1 What information do all safety officers use in their roles?

5.0 **How much time or effort is involved in making this decision?**

5.1 Are there minimum reaction times?

5.2 If so, then is it easy to meet the minimum reaction times?

6.0 **Are there any local work-arounds to compensate for workplace or technology deficiencies?**

6.1 What are the procedures built around deficiencies?

6.2 What information do you need to have with you that is not provided by the system?

6.3 Do you have to memorize anything?

7.0 **What display features may cause human errors? What are the consequences of those errors?**

7.1 What are the consequences associated with these errors?

8.0 **What kinds of additional aids might be useful? (For instance, predictive aids, alerts, warnings, automated function.)**

8.1 How do you mentally envision the vehicle state? Is it different from what is depicted?

Decision Requirements: Green Time

Interviewer:	Decision Designation What are the decisions made for starting Green Time?
Participant:	
Date:	
Start Time:	
End Time:	

1.0 **What is the overall goal of the decision?**

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1.1 Why does this decision have to be made?

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1.2 At what point in a launch is this decision made?

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2.0 **How is the decision made? What are the informational cues?**

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2.1 What information is needed?

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2.2 Where is the information located?

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2.3 How is this information depicted?

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2.5 What do you do before the launch to prepare for the decision?

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2.5 Do you reference any information sources outside the workstation?

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2.6 How can you predict it will go outside the boundaries?

2.7 Is the information easy to comprehend? Why or why not?

2.8 When is the information difficult to comprehend? Why?

3.0 **In what ways can the decision be difficult? Have there been cases where you were "on the fence"?**

3.1 If so, then what did it look like?

4.0 **How do you maintain situational awareness between all information sources when making this decision?**

4.1 What information do all safety officers use in their roles?

5.0 **How much time or effort is involved in making this decision?**

5.1 Are there minimum reaction times?

5.2 If so, then is it easy to meet the minimum reaction times?

6.0 **Are there any local work-arounds to compensate for workplace or technology deficiencies?**

6.1 What are the procedures built around deficiencies?

6.2 What information do you need to have with you that is not provided by the system?

6.3 Do you have to memorize anything?

7.0 **What display features may cause human errors? What are the consequences of those errors?**

7.1 What are the consequences associated with these errors?

8.0 **What kinds of additional aids might be useful? (For instance, predictive aids, alerts, warnings, automated function.)**

8.1 How do you mentally envision the vehicle state? Is it different from what is depicted?

Decision Requirements: Over the Shoulder

Interviewer:	Decision Designation Decide whether or not to destroy a vehicle during an "over the shoulder" scenario.
Participant:	
Date:	
Start Time:	
End Time:	

1.0 **What is the overall goal of the decision?**

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____

1.1 Why does this decision have to be made?

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____

1.2 At what point in a launch is this decision made?

____

____

2.0 **How is the decision made? What are the informational cues?**

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2.1 What information is needed?

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2.2 Where is the information located?

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2.3 How is this information depicted?

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2.5 What do you do before the launch to prepare for the decision?

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2.5 Do you reference any information sources outside the workstation?

____

____

2.6 How can you predict it will go outside the boundaries?

2.7 Is the information easy to comprehend? Why or why not?

2.8 When is the information difficult to comprehend? Why?

3.0 **In what ways can the decision be difficult, have there been cases where you were "on the fence?"**

3.1 If so, then what did it look like?

4.0 **How do you maintain situational awareness between all information sources when making this decision?**

4.1 What information do all safety officers use in their roles?

5.0 **How much time or effort is involved in making this decision?**

5.1 Are there minimum reaction times?

5.2 If so, then is it easy to meet the minimum reaction times?

6.0 **Are there any local work-arounds to compensate for workplace or technology deficiencies?**

6.1 What are the procedures built around deficiencies?

6.2 What information do you need to have with you that is not provided by the system?

6.3 Do you have to memorize anything?

7.0 **What display features may cause human errors? What are the consequences of those errors?**

7.1 What are the consequences associated with these errors?

8.0 **What kinds of additional aids might be useful? (For instance, predictive aids, alerts, warnings, automated function.)**

8.1 How do you mentally envision the vehicle state? Is it different from what is depicted?

Decision Requirements: Wind Corrected Trajectories

Interviewer:	Decision Designation Decide whether or not to destroy a vehicle during a "wind corrected trajectory" scenario.
Participant:	
Date:	
Start Time:	
End Time:	

1.0 **What is the overall goal of the decision?**

1.1 Why does this decision have to be made?

1.2 At what point in a launch is this decision made?

2.0 **How is the decision made? What are the informational cues?**

2.1 What information is needed?

2.2 Where is the information located?

2.3 How is this information depicted?

2.5 What do you do before the launch to prepare for the decision?

2.5 Do you reference any information sources outside the workstation?

2.6 How can you predict it will go outside the boundaries?

2.7 Is the information easy to comprehend? Why or why not?

2.8 When is the information difficult to comprehend? Why?

3.0 **In what ways can the decision be difficult? Have there been cases where you were "on the fence"?**

3.1 If so, then what did it look like?

4.0 **How do you maintain situational awareness between all information sources when making this decision?**

4.1 What information do all safety officers use in their roles?

5.0 **How much time or effort is involved in making this decision?**

5.1 Are there minimum reaction times?

5.2 If so, then is it easy to meet the minimum reaction times?

6.0 **Are there any local work-arounds to compensate for workplace or technology deficiencies?**

6.1 What are the procedures built around deficiencies?

6.2 What information do you need to have with you that is not provided by the system?

6.3 Do you have to memorize anything?

7.0 **What display features may cause human errors and what are the consequences of those errors?**

7.1 What are the consequences associated with these errors?

8.0 **What kinds of additional aids might be useful? (For instance, predictive aids, alerts, warnings, automated function.)**

8.1 How do you mentally envision the vehicle state? Is it different from what is depicted?

Action Requirements: Destroy Launch Vehicle

Interviewer:	Action Task Designation Take action to destroy a launch vehicle.
Participant:	
Date:	
Start Time:	
End Time:	

1.0 **What is the action sequence?**

1.1 At what point in a launch is this action executed?

2.0 **What cognitive activities are involved in this task/activity?**

2.1 Are there minimum reaction times?

2.2 If so, then is it easy to meet the minimum reaction times?

3.0 **In what ways can the activity be difficult?**

3.1 What about the support, or information depiction, makes the action sequence difficult?

3.2 Have you ever lost Situational Awareness in completing this task?

4.0 **What are the informational cues?**

4.1 How are the informational cues depicted?

4.2 Is the information easy to comprehend? Why or why not?

4.3 When is the information difficult to comprehend? Why?

5.0 **What is good or useful about the technology or aid used to complete this action?**

5.1 When can the technology, or aid, make action task completion difficult?

6.0 **Are there any local work-arounds to compensate for workplace or technology deficiencies?**

6.1 What are the procedures built around deficiencies?

6.2 What information do you need to have with you that is not provided by the system?

6.3 Do you have to memorize anything?

7.0 **What kinds of errors can be made during this action? What are their consequences?**

7.1 What errors have you seen in person?

7.2 What errors have you heard about in launches you were not involved with?

7.3 What are the consequences associated with these errors?

8.0 **What kinds of additional aids might be useful?**

8.1 Predictive aids?

8.2 Alerts or warnings?

8.3 Automated functions?

Appendix B. Documents Reviewed

WFF HSI Assessment—Documents Reviewed	
RDDS Program Documents	
1	ACDS Update_HF_Assessment_cg_4Mar19 (003).ppt
2	ChipRCCConceptEmail.pdf
3	Helfrich RSC Console 1.pdf
4	Range Data Display System Monthly Engineering Status Review, August 13, 2018
5	Range Safety Process for Programs and Projects. 800-PG-8715.5.1A. April 24, 2019
6	RDDS Mission Graphics Requirements_07252018
7	RDDS Schedule, July 17, 2018
8	RDDS Mission Graphics Software Requirements Review, September 11, 2018
9	v3_RDDS_Mission Graphics Requirements_08302017
10	Wallops Systems Software Engineering Branch (CODE 589) Collected Range Data Systems (CRDS) Software Management Plan/Product Plan, Version 1.0 (589-CRDS-BCSC-01-00), November 8, 2016
11	Wallops Systems Software Engineering Branch Software Requirements Review (SwRR) Checklist
12	WFF Safety Office Certification and Training Plan. 803-MGMT-PLN-INST-TRNG-01. July 31, 2016
Range Safety Documents	
13	RCC Safety Room Layout, 28Mar18.pptx
14	RCC Safety Room Upgrade_Feb18.xlsx
15	RCC Safety Room Layout White Paper. (2018). Wallops Flight Facility
16	Range Safety Operations Plan for the ANTARES OA-5 Mission Launched from WFF, Oct16, V.1
17	Flight Safety Plan for 46.021 UO Koehler, Version 01 (803-FS-FSP-SRPO-46.021-01), Effective Date August 2018
18	Range Safety Operations Plan for the 41.017 RockSatX Mission, Version 01 (803-RS-RSOP-SRPO-46.017), Effective Date August 2017
19	U12-0121-301 Wallops Island—Safety Room-RevC
20	RSM2002C Range Safety Manual for Goddard Space Flight Center (GSFC) Wallops Flight Facility (WFF), March 15, 2013
21	RSO Training Module 1. Course Overview, Range Flight Safety Operations. Slide 55 RSO Roles and Responsibilities. Received during RSO Training, August 2018.
22	RSO Training Module 2. Unguided Launch Vehicle Fundamentals
23	RSO Training Module 3. Unmanned Aircraft System Fundamentals
24	RSO Training Module 4. Guided Launch Vehicle Fundamentals

External (Non-NASA) Range Safety Operations Documents	
25	US Air Force Requirements Strategy Review of CPD for the National Security Space Essential Range (NSSER)
26	(USAF) CDSEG Flight Operations for the Range Standardization & Automation Phase IIA of the Spacelift Range System (SLRS), RF-000112, August 10, 2007
27	(USAF) Concept of Operations for the Mission Flight Control Center System, May 20, 2011
28	(USAF) Mission Flight Control Officer Lesson Plan: Perform Routine Crew Actions, October 13, 2015
29	(USAF) Mission Flight Control Officer Lesson Plan: Understand Range Display Fundamentals, October 13, 2015
30	NASC NAVAIR Point Mugu Sea Range Overview, September 5, 2018
31	NASC NAVAIR Common Display System, September 5, 2018
Government Standards and Documents	
32	14 CFR 417.3 [Title 14 Aeronautics and Space; Chapter III Commercial Space Transportation, Federal Aviation Administration, Department of Transportation (Parts 400-499); Subchapter C Licensing; Part 417 Launch Safety; Subpart A General and License Terms and Conditions]
33	Ahlstrom, V. (2016). Human Factors Design Standard (DOT/FAA/HF-STD-001B). Atlantic City International Airport, NJ: Federal Aviation Administration William J. Hughes Technical Center
34	Ahlstrom, V., & Kudrick, B. (2007). *Human Factors Criteria for Displays: A Human Factors Design Standard Update of Chapter 5.* (DOT/FAA/TC-07/11). Atlantic City International Airport, NJ: Federal Aviation Administration William J. Hughes Technical Center
35	Department of Defense (DoD). (2012). *MIL-STD-1472G Department of Defense Design Criteria Standard: Human Engineering*, Washington, D.C.
36	Department of Defense (DoD). (2015). *MIL-STD-1474E: Department of Defense Design Criteria Standard Noise Limits*, Washington, D.C.
37	Department of Transportation Volpe Center. (1995). *Human Factors in the Design and Evaluation of Air Traffic Control Systems, DOT-VNTSC-FAA-95-3*, Final Report
38	Department of Transportation. Federal Highway Administration (FHA). Human Factors Design Guidelines for Advanced Traveler Information Systems (ATIS) and Commercial Vehicle Operations (CVO). Chapter 11: Equations. Publication Number: FHWA-RD-98-057. Washington, D.C.
39	Department of Transportation. Federal Aviation Administration (FAA). (2014). Electronic Flight Displays. AC 25-11B, Washington, D.C.
40	Department of Transportation. Federal Aviation Administration (FAA). (2013). Installed Systems and Equipment for Use by the Flightcrew. AC 25.1302-1, Washington, D.C.

41	EPRI and the U.S. Department of Energy. (2004). *Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification: Guidelines for Planning, Specification, Design, Licensing, Implementation, Training, Operation, and Maintenance.* Palo Alto, CA: EPRI and U.S. DoE
42	Goddard Space Flight Center (GSFC) Wallops Flight Facility Range Safety Manual (RSM). GSFC-STD-8009. February, 2019
43	NASA Presentation (given by David Tow) to International Test and Evaluation Association Conference, 2011
44	NASA 840-HDBK-0003 Wallops Flight Facility Range User's Handbook, September 10, 2013
45	NASA RSM2002C Range Safety Manual for Goddard Space Flight Center (GSFC) Wallops Flight Facility (WFF), March 15, 2013
46	NASA Human Integration Design Handbook (HIDH)-NASA (Vol. 3407). SP-2010, Washington, D.C.
47	NASA/SP-2015-3709 Human Systems Integration (HSI) Practitioner's Guide, November 1, 2015
48	NASA/SP-2016-6105 NASA Systems Engineering Handbook, Rev. 2, February 2017
49	NPR 7123.1B NASA Systems Engineering Processes and Requirements, April 18, 2013
50	NPR 8715.5B Range Flight Safety Program, 2018
51	NASA-STD-8719.25 Range Flight Safety Requirements, February 5, 2018
52	NASA/TM-2006-214535/NESC-RP-06-108/05-173-E Design, Development, Testing and Evaluation: Human Factors Engineering
53	National Aeronautics and Space Administration (NASA). Ames Research Center. Guidelines for Color Discrimination and Identification. Using Color in Information Display Graphics. Color Usage Research Lab. colorusage.arc.nasa.gov/guidelines_discrim_id.php
54	National Aeronautics and Space Administration (NASA). Ames Research Center Color Usage Research Lab. Using Color in Information Display Graphics: Luminance Contrast. colorusage.arc.nasa.gov/luminance_cont.php
55	Nuclear Regulatory Commission. (2002). *Human-System Interface Design Review Guidelines*, NUREG-0700 Rev. 2, Washington, D.C.
56	Nuclear Regulatory Commission. (2012). Human Factors Engineering Program Review Model, NUREG-0711, Rev. 3, Washington, D.C.
57	NUREG-CR-2623 The Allocation of Functions in Man-Machine Systems: A Perspective and Literature Review
58	Physical and Technical Security Standards for Sensitive Compartmentalized Information Facilities, 17 September 2010, IC STD/ICS 705-1
59	Technical Specifications for Construction and Management of Sensitive Compartmented Information Facilities, Version 1.4, IC Tech Spec-for ICD/ICS 705

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14. ABSTRACT
NASA Wallops Flight Facility (WFF) is undergoing a major upgrade to its Mission Graphics System and Flight Termination System (FTS) within the Range Control Center Range Safety Room under two separate projects. The WFF Range and Mission Management Office requested the NASA Engineering and Safety Center (NESC) to assess system prototypes. However, due to the absence of available prototypes, the NESC team adjusted the scope to provide best practices and guidance documents. This report provides Human Systems Integration guidance based on best practices that should lead to more efficient and effective operations in the Range Safety Room.

15. SUBJECT TERMS
Flight Termination System; Mission Graphics System; NASA Engineering and Safety Center; Range Data Display System

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