

Flight Critical Control Valves, Military Aircraft

RATIONALE

This aerospace recommended practice is issued to establish more uniform and technically efficient processes for the design, qualification and manufacture of Flight Critical Control Valves (FCCV's).

FORWARD

The primary application of FCCV's has been for helicopter flight critical control servoactuators which are used to continuously control rotor blade pitch. The single FCCV controls multiple servoactuator power stages to simplify redundancy management, minimize installation envelope and minimize weight. Although this specification is primarily focused on helicopter application, it may be used for design guidance on other types of flight control servoactuators (e.g., fighter aircraft, missile, unmanned aircraft), hydraulic system switching valves and mission critical utility system control valves.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) provides guidance in the design, development, qualification test, process control and production acceptance test for flight critical control valve (FCCV) design used in military flight control servoactuators where loss of single valve control could cause a catastrophic failure resulting in death, permanent total disability, and/or financial loss exceeding a defined contractual limit. The FCCV, which is one element of a flight control actuator servo control loop, is a variable position control valve which modulates fluid into and out of the servoactuator power stage cylinders. The FCCV may be mechanically driven by either a mechanical flight control system as shown in Figure 1 or hydraulically driven from electro-hydraulic servo valve (EHSV) modulation control flow as shown in Figure 2. This type of control valve is not an EHSV or a direct drive valve (DDV).

The FCCV is used in military hydraulic systems which conform to AS5440.

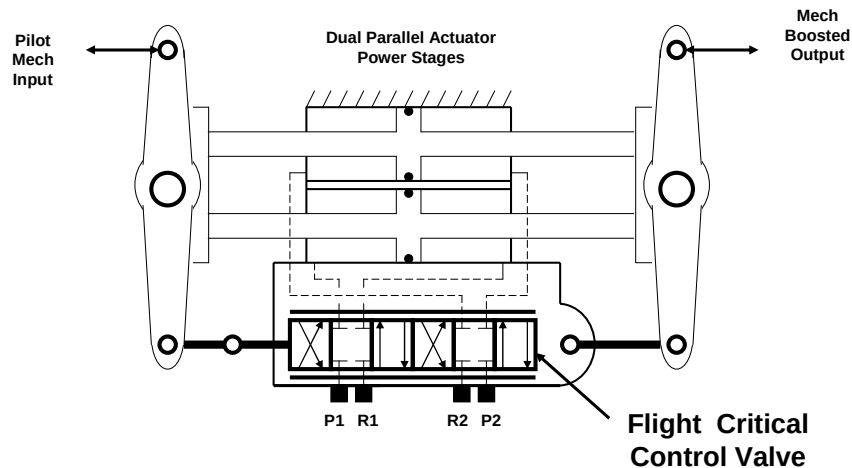


FIGURE 1 - HYDRO-MECHANICAL SERVOACTUATOR FLIGHT CRITICAL CONTROL VALVE

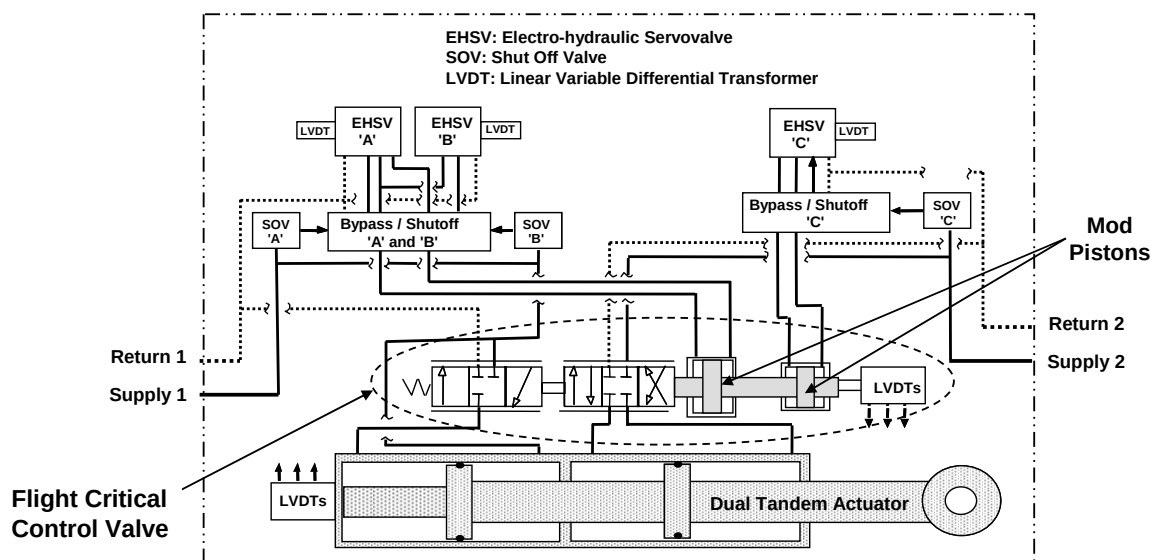


FIGURE 2 - FLY-BY-WIRE (FBW) SERVOACTUATOR FLIGHT CRITICAL CONTROL VALVE

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AIR1243	Anti Blow-By Design Practice for Cap Seals
ARP1383	Aerospace - Impulse Testing of Hydraulic Components
AS4059	Aerospace Fluid Power - Cleanliness Classification for Hydraulic Fluids
ARP4386	Terminology and Definitions for Aerospace Fluid Power, Actuation and Control Technologies
AIR4543	Aerospace Hydraulics and Actuation Lessons Learned
AS4716	Gland Design, O-ring and Other Elastomeric Seals
ARP4904	Capability Guidelines for Computer Controlled Test Equipment for Hydraulic Components
AIR5273	Actuation System Failure Detection Methods
AS5440	Hydraulic Systems, Military Aircraft, Design and Installation, Requirements For
ARP5580	Recommended Failure Modes and Effects Analysis (FMEA) Practices for Non-Automobile Applications
ARP5941	Aerospace Fluid Power - Contamination Sensitivity - Considerations for Establishing Test Procedures for Flight Control Actuators
AS8775	Hydraulic System Components, Aircraft and Missiles, General Specification For
AS9017	Control of Aviation Critical Safety Items
AS9100	Quality Management Systems - Requirements for Aviation, Space and Defense Organizations
AS9102	Aerospace First Article Inspection Requirement
AMS2700	Passivation of Corrosion Resistant Steels
AMS2759/5	Heat Treatment Martensitic Corrosion-Resistant Steel Parts
AMS3216	Fluorocarbon (FKM) Rubber, High-Temperature-Fluid Resistant Low Compression Set 70-80
AMS3218	Fluorocarbon (FKM) Rubber, High-Temperature-Fluid Resistant Low Compression Set 85-95

AMS5630	Steel, Corrosion-Resistant, Bars, Wire and Forgings, 17Cr - 0.52Mo (0.95 - 1.2C) (440C)
AMS7259	Rubber: Fluorocarbon (FKM) High Temperature/Fluid Resistant Low Compression Set/85 to 95 Hardness For Seals in Fuel Systems and Specific Engine Oil Systems
AMS7276	Rubber: Fluorocarbon (FKM) High-Temperature-Fluid Resistant Low Compression Set For Seals in Fuel Systems and Specific Engine Oil Systems
AMS-P-83461	Packing, Preformed, Petroleum Hydraulic Fluid Resistant, Improved Performance at 275°F (135°C)
AMS-R-83485	Rubber, Fluorocarbon Elastomer, Improved Performance at Low Temperatures
JA1000	Reliability Program Standard
JA1000-1	Reliability Program Standard Implementation Guide

2.1.2 U.S. Government Publications

Unless otherwise recommended, the issues of these documents are those listed in the issue of the Department of Defense Index of Specifications and Standards (DoDISS) and supplement thereto, cited in the solicitation.

Specifications are available from the the Standardization Document Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, <http://assist.daps.dla.mil/quicksearch/>

2.1.2.1 Active Specifications

MIL-STD-882	Department of Defense Standard Practice: System Safety
MIL-PRF-6083	Hydraulic Fluid, Petroleum Base, For Preservation and Operation
MIL-PRF-46170	Hydraulic Fluid, Rust Inhibited, Fire Resistant, Synthetic Hydrocarbon base
DI-SAFT-80101	Subsystem Hazard Analysis Report
MIL-PRF-83282	Hydraulic Fluid, Fire Resistant, Synthetic Hydrocarbon Base, Aircraft, Metric, NATO Code Number H-537
MIL-PRF-87257	Hydraulic Fluid, Fire Resistant; Low Temperature, Synthetic Hydrocarbon Base, Aircraft and Missile Standards

2.1.2.2 Cancelled Specifications

The following publications are provided for information purposes only and are not a part of this SAE Aerospace Technical Report. The subscribing agency may use these documents as guidance or invoke them as necessary.

MIL-STD-756	Reliability Modeling and Prediction
MIL-STD-785	Reliability Program for Systems and Equipment Development and Production
MIL-STD-1629	Procedures for Performing a Failure Mode and Criticality Analysis
ISO 10012-1	Quality assurance requirements for measuring equipment - Part 1: Metrological confirmation system for measuring equipment
ANSI Z540-1	Calibration Laboratories and Measuring and Test Equipment General Requirements

2.1.2.3 Regulations

AMCOM 702-7 Flight Safety Parts/New Source Testing Program Management. Note: This regulation is approved for public release and is available from the U.S. Army Aviation and Missile Command (AMCOM), Redstone Arsenal, AL 35898-5000.

2.1.2.4 Handbooks

PR11-515 Joint Aeronautical Commanders Group Public Release, Aviation Critical Safety Item Management Handbook

2.1.3 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM E1417 Standard Practice for Liquid Penetrant Testing

ASTM E1444 Standard Practice for Magnetic Particle Testing

ASTM D1744 Test Method for Water in Liquid Petroleum Products by Karl Fischer Reagent

2.1.4 Industry Standards

Available from Electronic Industries Alliance, 2500 Wilson Boulevard, Arlington, VA 22201-3834, Tel: 703-907-7500, www.eia.org.

EIA 649 Configuration Management Standard

2.2 Applicable References

"Aircraft Flight Control Actuation System Design", E.T Raymond and C.C. Chenoweth, SAE Publication

2.3 Definitions

General definitions for terminology used within this document may be found in ARP4386. The following definitions are unique to this document.

2.3.1 CONTRACTOR

The company or other organization on contract to the Government Procuring Activity, to design, develop, manufacture and qualify a flight critical control valve. The Contractor typically writes a servoactuator specification and sub-contracts the detail design of the servoactuator and flight critical control valve to a Supplier.

2.3.2 CRITICAL CHARACTERISTIC (CC)

Any feature throughout the life cycle of a critical safety item (e.g., dimension, tolerance, finish, material or assembly, manufacturing or inspection process, operation field maintenance, depot overhaul requirement) that if nonconforming, missing, or degraded may cause the failure or malfunction of the critical safety item.

2.3.3 CRITICAL SAFETY ITEM (CSI)

Any part, assembly, or installation that contains a characteristic which failure, malfunction, or absence of could cause a catastrophic failure resulting in death, permanent total disability, and/or financial loss exceeding a defined contractual limit. Within industry, a critical safety item is sometimes referred to as a flight critical part or a flight safety part.

2.3.4 FLIGHT CRITICAL CONTROL VALVE (FCCV)

An assembly which contains one or more critical safety items used to meter hydraulic fluid into and out of redundant force summed servoactuators. Figure 1 and 2 show examples of FCCV's used in a hydro-mechanical servoactuator and a fly-by-wire servoactuator, respectively.

Wherever this ARP uses the terminology "flight critical control valve", it should be interpreted to mean all of the functional elements of the control valve assembly which can affect its performance. This includes but is not limited to the inlet screen, spool, sleeve, body manifolds, modulation pistons, spring assemblies, seal assemblies and integral sensors.

2.3.5 MODULATION (MOD) PISTON

Hydraulic pistons used to drive the servoactuator control valve as shown in Figure 2. The mod pistons are typically controlled by electro-hydraulic servovalves (EHSV's).

2.3.6 ACTUATOR POWER STAGE CYLINDER

The piston and cylinder assembly which converts the hydraulic power from one hydraulic system into usable mechanical output power. Multiple power stages can be arranged in parallel as shown in Figure 1, or in tandem (series) as shown in Figure 2.

2.3.7 PERFORMANCE

Wherever this ARP uses the term "performance" it should be considered as the functional design and test capabilities of the FCCV as defined under the Performance Tests section of the Acceptance Test section.

2.3.8 PROCURING ACTIVITY

The Government agency responsible for procuring the aircraft in which the FCCV is used.

2.3.9 SUPPLIER

The company or other organization to which the Contractor subcontracts some part of the tasks required to design, develop, manufacture and qualify a FCCV.

2.4 Acronyms and Their Definitions

ATP	Acceptance Test Procedure
CC	Critical Characteristic
CCRB	Critical Characteristic Control Board
CDR	Critical Design Review
CSI	Critical Safety Item
CSICB	Critical Safety Item Control Board
CSIPRG	Critical Safety Item Program
EDM	Electrical Discharge Machining
FAI	First Article Inspection

FBW	Fly by Wire
FCCV	Flight Critical Control Valve
FEA	Finite Element Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FPRB	Frozen Planning Review Board
ID	Inside Diameter
LVDT	Linear Variable Differential Transformer
NDI	Non Destructive Test and Inspection
OD	Outside Diameter
PDR	Preliminary Design Review
PEEK	Polyetheretherketone
ppm	Parts per Million
PTFE	Polytetrafluoroethylene

3. REQUIREMENTS

3.1 General Design

The FCCV design should be as simple and foolproof as possible and should operate under the combined conditions, forces and stresses that the aircraft may impose throughout the environment, performance envelope, structural limitations and design life of the aircraft.

The FCCV should not bind, jam or cause detrimental performance when subjected to the recommended requirements of this document.

All components used in the FCCV should conform to AS8775 and its applicable detailed specifications, except the requirements should be upgraded to agree with the selected operating and test pressures and any other superseding requirements defined within this specification.

For additional control valve design guidance and lessons learned, see:

1. SAE publication "Aircraft Flight Control Actuation System Design," Section 9 "Power Control Unit and Power Drive Unit Design Guidelines."
2. AIR4543, Aerospace Hydraulics and Actuation Lessons Learned

3.1.1 Design Process

3.1.1.1 Preliminary Design Review (PDR)

The following information should be provided in support of the PDR:

1. Layouts including functional schematics, envelope drawings and cross sections with proposed seals, valve strokes, spool diameters, flow slot sizes, driving force, chip shear capability and spool sleeve clearances.
2. Detailed drawings of key components.
3. Preliminary material and process specifications should be identified on the drawings.
4. Preliminary analysis for pressure drop, performance, electrical, stress and finite element analysis (FEA).
5. Preliminary Producibility, Subsystem Hazard, Reliability Prediction, Maintainability and Failure Mode, Effects and Criticality Analysis.
6. Candidate Critical Safety Items and their Critical Characteristics.

All PDR action items should be closed by the Critical Design Review.

3.1.1.2 Critical Design Review (CDR)

All development test data should be available by CDR.

The following information should be provided in support of the CDR:

1. Overview of development testing.
2. Critical Safety Items should be identified along with their Critical Characteristics on engineering documents and drawings.
3. Completed detailed drawings signed off by the Design, Check, Project, Stress, Reliability, Maintainability, Quality, Materials and Process and Manufacturing engineering disciplines.
4. Completed Producibility Analysis, Subsystem Hazard Analysis, Reliability Prediction Analysis, Failure Mode, Effects and Criticality Analysis and the Maintainability Analysis signed off by all applicable engineering disciplines.
5. Final pressure drop, performance, electrical, stress and FEA analysis.
6. New process specifications which are signed off by all applicable engineering disciplines.

All CDR action items should be closed before the manufacturing of qualification components.

3.1.2 Hydraulic Fluid

The FCCV should be designed to operate with hydraulic fluid conforming to MIL-PRF-83282 and MIL-PRF-87257.

3.1.3 Performance Over Temperature

The FCCV should meet performance requirements (operating load, rate, stroke, response, flow, shut off, turn on, etc.) under minimum and maximum fluid and ambient operating temperatures. Single undetected and non-isolatable system failures should be considered when determining minimum and maximum FCCV operating fluid temperatures (e.g., failed thermal control valves, hardover main pumps, and fail opened supply system pressure relief valves).

3.1.3.1 Fluid Thermal Shock

The FCCV should be capable of full performance during and after the worst-case thermal shock condition which may exist. Examples of cold fluid shock include cold fluid flowing into the FCCV after an alternate cold hydraulic system is switched in or following the operation of a large stagnant cold utility circuit (e.g., landing gear). Hot fluid shock should also be considered. Examples of hot fluid shock include hot fluid flowing into the FCCV after an alternate hot hydraulic system is switched in or when a cold soaked dormant actuator becomes active. Appropriate analysis should be performed to establish the worst-case temperature shock conditions.

3.1.3.2 Differential System Fluid Temperature

The FCCV should be capable of full performance during and after worst-case fluid temperature and worst-case differential fluid temperature which may occur between the redundant hydraulic systems connected to it. The design of the FCCV should consider the combined effects of fluid thermal shock in conjunction with differential system fluid temperature conditions. Appropriate analysis should be performed to establish conservative worst-case differential temperatures.

3.1.4 Pressure

3.1.4.1 Proof Pressure

3.1.4.1.1 Supply Proof Pressure

Proof pressure should be equal to $1.5 \times$ nominal operating supply pressure or the peak pressure which may occur over life. The peak pressure should be established conservatively and the FCCV should be capable of operating when subjected to proof pressure. There should be no evidence of external leakage, other than a slight wetting at seals insufficient to form a drop and no yielding of components.

The following conditions should be considered when determining the proof pressure magnitude:

- a. Pressure resulting when each actuator powerstage is lost (failed) under maximum in-flight load condition and the remaining powerstage or powerstages must immediately carry the resulting load.
- b. Supply pressure spiking caused by rapid closing of the FCCV when under high flow rate.
- c. Supply pressure spiking caused by a rapid closing valve in a parallel circuit. Specific attention should be given to leak isolation control valves which can quickly shut off high flow rates following a fully fractured line or hose.
- d. Maximum supply pressure with hydraulic system relief valve at maximum full flow pressure over temperature range $\times 1.1$ (hard over pump failure condition).
- e. Pressure amplification which may occur from the use of an unbalanced piston area.

3.1.4.1.2 Return Proof Pressure

Return proof pressure should equal the nominal supply operating pressure. There should be no evidence of external leakage, other than a slight wetting at seals insufficient to form a drop and no yielding of components.

3.1.4.2 Burst Pressure

Burst pressure should be equal to $1.67 \times$ proof pressure. There should be no evidence of external leakage, other than a slight wetting at seals insufficient to form a drop or rupture of any component. Yielding of materials is acceptable.

3.1.4.3 Maximum Differential Pressure

The FCCV should be capable of operating over full stroke, including shut off and turn on, at proof pressure and zero return pressure without causing damage to the FCCV (e.g., detrimental galling, leakage or yielding).

Following maximum differential pressure operation, the FCCV should meet performance requirements including shut off and turn on when operating at nominal supply and return pressures.

3.1.4.4 Minimum Differential Pressure

The FCCV should be capable of operating over full stroke, including shut off and turn on when operating at 90% of the minimum possible supply pressure and 110% of the maximum possible return pressure. Pressure drop, pressure droop, system shutdown/failure pressure and use of pumps with operating pressure lower than the main pump should be considered for supply. Back pressure should be considered for return. Ground cart operation should also be considered as it has additional hose, line and component pressure drops, and response time may differ from the aircraft system.

Appropriate performance requirements should be established where minimum differential pressure operation can be detrimental to safety. Areas for consideration include FCCV single system operation, valve driving force and chip shear capability as applicable.

3.1.4.5 Maximum Supply and Maximum Return Pressure

The FCCV should be capable of operating over full stroke, including shut off and turn on when subjected to 110% of maximum supply pressure (e.g., system supply relief valve full flow pressure x 1.1) and 110% of maximum return pressure without causing damage to the FCCV (e.g., detrimental galling, leakage, or yielding).

Appropriate performance requirements should be established where maximum supply and maximum return pressure can be detrimental to safety. Areas for consideration include hardover main pump failure modes.

3.1.4.6 Fatigue

There are essentially three operating conditions where fatigue must be considered: (1) pressure impulse (2) mod piston force fighting, and (3) valve bottoming. The FCCV should not initiate a crack or fail to meet performance requirements when subjected to impulse pressure stresses, mod piston force fighting stresses and valve bottoming stresses. There are two basic methods which can be used to establish appropriate fatigue test requirements: (1) specifically derived and (2) generically derived.

3.1.4.6.1 Specifically Derived Method

Specifically derived test requirements can be established by conservatively and rigorously developing a load/pressure test cycle spectrum based on evaluation of all FCCV operating conditions. Temperature conditions should be factored into the test spectrum. The spectrum should be developed to ensure that less than 1 CSI in 1 million will fail within its established safe-life retirement time. Within industry, this well-known design philosophy for CSI's is also called six-nines fatigue reliability (1 minus 1/1 000 000 failure rate). There should be a minimum of six test specimens for CSI's. The development of the test spectrum must consider all variables which can affect the overall fatigue life of the component, including but not limited to:

- a. Material strength variables (composition, dimensional, quality control, grain axis, etc.)
- b. Load variables (measurement accuracy and maneuver variability)
- c. Usage variables (environment, velocity, corrosion, wear, etc.)
- d. Test inaccuracies

3.1.4.6.2 Generically Derived Method

Generically derived test requirements avoid the extensive analytical effort needed to develop specifically derived test requirements while maintaining conservative safety margins and avoiding significant impact to the overall design. Generically derived requirements are provided in the following paragraphs for impulse pressure, mod piston force fight and valve bottoming.

5 to 25% of the cycles should be at the maximum fluid temperature with the remaining at the maximum operating temperature (non-system failure condition) to test metal materials and non-metal materials at their weakest conditions and largest seal extrusion gaps. The higher temperature testing also ensures seals do not degrade, weaken, leak, and fail in service.

The FCCV should pass ATP after testing and should show no indication of cracking, excessive seal extrusion/damage or component material yielding during the tear down inspection.

3.1.4.6.2.1 Impulse Pressure

All passages should be appropriately exposed to supply and return impulse pressure testing in accordance with ARP1383. The supply impulse pressure should be applied independently of the return pressure to achieve maximum differential pressure across FCCV elements and seals. The FCCV should be tested in all operating positions (i.e., null, full extend and full retract) and all possible operating conditions.

The supply and return ports, passages and components should be tested to the generically derived number of pressure impulse cycles defined below:

- a. CSI supply and cylinder ports, passages and components: 1 000 000 cycles at 1.5 x nominal operating supply pressure plus 5000 cycles at proof pressure. There should be a minimum of six test specimens to verify this requirement.
- b. Non CSI supply and cylinder ports, passages and components: 300 000 cycles at 1.5 x nominal operating supply pressure plus 5000 cycles at proof pressure. There should be a minimum of two test specimens to verify this requirement.
- c. Return ports, passages and components subjected to return pressure only: 300 000 cycles at nominal operating supply pressure. There should be a minimum of two specimens to verify this requirement.

3.1.4.6.2.2 Mod Piston Force Fighting

The FCCV mod pistons will force fight throughout life. The affected parts should be designed to withstand the following test requirement:

- a. 1 000 000 tension/compression cycles at 150% of normal operating pressure
- b. 5000 tension/compression cycles at proof pressure.

The alternating mod piston stress load should be reversed from tension to compression for each test cycle to provide an R ratio of -1. In other words, the test should not perform 1 000 000 cycles in a tension direction then 1 000 000 cycles in a compression direction as this would result in an R ratio of 0.

This test should be verified by testing a minimum of 6 CSI specimens and a minimum of two non CSI specimens.