REALIZATION OF A PROTOTYPE FULL-SCALE TEST RIG TOWARD QUALIFICATION OF HIGH-STRENGTH HEPA FILTER UNITS

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Abstract

The American Society of Mechanical Engineers (ASME) International's AG-1[(1)], the Code on Nuclear Air and Gas Treatment, defines qualification test specifications for components in air- and gas-cleaning systems of nuclear facilities. Key components used to confine radioactive and toxic airborne particles within controlled areas of nuclear facilities are High Efficiency Particulate Air (HEPA) filter units. AG-1 Sections FC (*HEPA Filters*) and FK (*Special HEPA Filters*) cover conventional nuclear-grade filters having a filter medium of submicron glass fibers. A new code section is currently under development to address the limitations of conventional filters for select nuclear applications and service conditions. Designated as Section FM and titled, *High Strength HEPA Filters*, it is intended to provide performance specifications for the qualification of nuclear-grade HEPA filters having a glass-fiber filter medium reinforced by a cloth of glass fibers.

One of the essential steps in the filter qualification sequence proposed for Section FM is the resistance to pressure-impulse test which is intended to verify values for the proof strength of high-strength filters in a wet condition. In order to establish filter burst strength levels- upon which proof strength values are based - a prototype, full-scale test rig needed to be designed and built. This rig is foreseen to also serve as the direct precursor to a full-scale filter qualification test stand, eventually to be located at the Edgewood Chemical Biological Center of Aberdeen Proving Ground.

Tests on intermediate-scale filters had proven the suitability of the so-called falling-water-column concept, upon which the test rig is based. The concept itself calls for the quick release of an initially stationary column of water into free fall through a vertical distance and onto the test filter. To help reduce the height of the test rig without compromising the required magnitude of the pressure impulse, it was necessary to accelerate the mass of water by more than the 1 g available from the effect of gravity alone. To this end, expanding compressed air is anticipated to be used above the water mass as a propellent medium.

Realization of the test rig was achieved within the framework of a senior capstone design project toward fulfillment of the academic requirements for a Bachelor of Science degree in Engineering Technology (Mechanical option). The goals of the project included the design and fabrication of a full-scale prototype filter-test rig. Among important aspects taken into consideration were constraints intrinsic to the planned location of the future filter qualification test stand at Edgewood. In particular, these included space limitations and stringent environmental and safety regulations.

Reported here is a documentation of the highlights of the design process to include design options evaluated and relevant aspects of the test rig laid out for eventual routine qualification of 610-mm x 610-mm x 292-mm (24-in x 24-in x $11^1/_2$-in) filter units. An analysis of material costs for rig fabrication, as well as a compilation of rig characteristics are provided.

Introduction

Ventilation and air cleaning systems provide for the health safety and the thermal comfort of personnel in facilities that contain hazardous or toxic radioactive materials. The air cleaning systems also prevent the release of contaminated airborne particulate and gases to the surrounding environment. In such systems, the required high particle removal efficiencies at relatively low pressure drops are made possible by the use of nuclear-grade HEPA filter units. Under benign operating conditions, HEPA filters serve globally as reliable and economical components in the air cleaning systems of nuclear facilities.

As part of the containment barrier between contaminated zones and the environment, HEPA filters must be relied upon not only during normal facility operations, but also under possible abnormal or so-called accident, or upset conditions. Filter units may be called upon to withstand individual, or combined challenges of elevated temperature, pressure drop, or air relative humidity: ideally without performance decreases that would result in unacceptable losses of particle containment or confinement. The effects of earthquakes, tornados, fires, fire-suppression measures, as well as explosion-induced shock waves, also represent challenges that may need to be taken into consideration toward ensuring for the protection of filters in their service locations.

Filter Qualification

Within the most common filter designs for nuclear applications - qualified in accordance with Mandatory Appendix FC-I of ASME's AG-1 - the filter medium consists of a fragile 0.5-mm (0.015-in) thick mat of submicron diameter glass fibers. Filter units are currently qualified as nuclear grade to Sections FC (*HEPA Filters*) and FK (*Special HEPA Filters*) of ASME's AG-1 Code[1]. These code sections serve to specify minimum performance levels for qualification of conventional filter designs which incorporate a filter medium of glass fibers having no significant strength-augmenting reinforcement. Sections FC and FK for conventional filters include the so-called resistance-to-pressure test as one important step. Its function is to verify a quite modest, minimum filter strength value for qualification purposes.

Currently a new AG-1 Code Section (FM) with Mandatory Appendix FM-I is under development for high-strength HEPA filters and high-strength filter media. It includes performance specifications for Level I filters which are outfitted with a glass-fiber filter medium reinforced by a cloth of glass fibers. Also specified are requirements for more robust, Level II filters, which incorporate additional measures to counteract in-service loosening of the filter pack. Their increased filter-pack stability can provide for longer service intervals, or higher reliability under more adverse operating conditions. Non-mandatory guidelines for both filter shelf and service life, as well as for safety-margin calculations are also proposed aspects of Section FM.

Pressure-impulse test

For the qualification of high-strength filters, a sufficiently stringent test analogous to the resistance-to-pressure test of Sections FC and FK was required. The primary function is to serve as a proof test to verify a minimum wet-filter burst strength. The test concept under evaluation and development prior the beginning of this project was that of the so-called falling water column (s. Fig. 1). The original insight for this concept is attributed to *Stillo* in 2007[2]. The underlying fundamental principle involves the storage of potential energy in a rising column of water over a time interval of tens of minutes, followed by a rapid conversion into kinetic energy by the quick opening a valve. The kinetic energy of the falling water is then applied to the upstream face of the test filter. As a result, a pressure impulse with a rise time of $<$400 ms can be generated across the test filter. As initially visualized, gravity was to be the sole agent of acceleration for the water column.

Project Goals and Constraints

There are currently no US or international codes in place for the qualification of high-strength, nuclear-grade HEPA filters. Toward this end, the primary goal for the project was to bring into realization a full-scale prototype test rig to help qualify filter units as being of high strength. The function of the test rig is to determine representative burst and proof strengths for the proposed Level I and the Level II filters.

Project constraints were all related to available resources. These included personnel in the form of team members and the total of 100 h to be allocated by each toward the project. The four months of an academic semester within which the project was to be carried out and a budget of some $10,000 for materials represented the other major constraints.

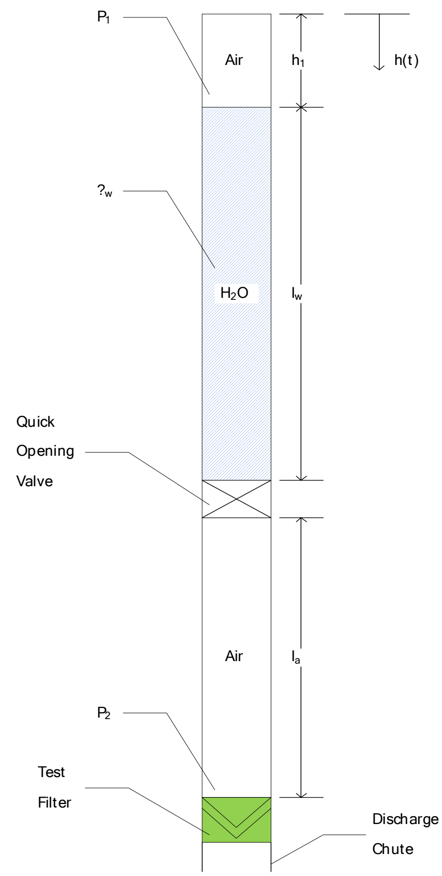

Figure 1: Schematic of falling water column concept for qualification testing of high-strength nuclear-grade HEPA filters[3].

Methodology and Major Milestones

At the beginning of the project, the team established a plan and a list of major tasks to be accomplished. These included the following.

- develop a plan-of-action with projected milestones and deadlines
- survey relevant technical literature on the topic
- identify project constraints and rig design specifications
- apply brainstorming techniques
- keep relevant aspects of health, safety, and ergonomics closely in mind during all project phases
- settle on a test method suitable for a pressure-impulse qualification test
- choose an appropriate test rig concept
- develop design alternatives for the test rig
- conduct technical and economic analyses for each design
- select the most suitable of the design alternatives
- have the feasibility of the selected design verified in a design review
- purchase the parts and materials for the final design
- fabricate test rig components and assemble them
- conduct shakedown tests on the prototype rig, time permitting
- compile all relevant design data
- document progress in journals and the results in a final report
- orally present project results to the Mechanical Engineering Technology Faculty

Design Process

Considerations and Criteria

The outside case dimensions of the most commonly used nuclear-grade HEPA filters are 610-mm x 610-mm x 292-mm (12-in x 12-in x $11^{1/}{}_{2}$-in) for rated flows between 1700 m^3/h (1000 ft^3/min) and 2250 m^3/h (1500 ft^3/min). Thus, the test rig was laid out for this case size. Other design criteria included maximum allowable overall dimensions of the test rig, the need for rig transportability, prospective wind loads, and relevant codes and standards, as well as environmental and safety[4] standards.

The test rig needed to be easily transportable for later relocation to Aberdeen Proving Ground, once it has been modified to become the test stand for routine qualification testing. To fit within the interior of an available building there, its dimensions could not exceed 4.3 m x 4.6 m x 5.2 m tall (14 ft x 15 ft x 17 ft tall). Any valve selected was expected to be able to be opened completely within approx. 500 ms. From the perspective of resource conservation, utility (energy and water) requirements were expected to be kept to a minimum. Toward attaining a relatively uniform differential-pressure distribution over the cross-section of the the test filter, it was anticipated that a round-to-square transition piece located between the valve and the test filter would be required.

Wind load calculations for the Aberdeen location were based upon 190-kph (120-mph) gusts. These, toward the selection of anchor bolts and the design of the concrete support slab and optional side braces, in case the final location were to become one outside. Given risks to human safety, any pressurized parts of the test apparatus were to be designed with a safety factor of at least five (5), backed up by pressure relief valves.

Literature

For test-rig design orientation, published failure Δp's of high-strength filters were sought. Values for one documented Level II design could be roughly estimated to lie between >15 kPa (differential) (2.2 psid) as measured after extended exposure to supersaturated airflows and <44 kPa (differential) (6.4 psid) resulting from shock-wave impingement in dry air(5). Failure values for one Level I filter design of the same pack dimensions were reported to be 10 kPa (1.45 psid) in super-saturated airflows (fog conditions) and 30 kPa (4.35 psid) in dry air at high velocity(6). Since filters undergoing qualification need to withstand the intended pressure impulse while in a wet condition and none of the above burst-strength values represent the challenge of a pressure impulse, they provided only rough estimates for use in the design of a pressure-impulse-based test rig. So better representative data were needed. These were found to be available from results of in-house tests on intermediate-scale filters.

Results of pressure-impulse tests on conventional and high-strength filters and filter media samples (smaller-scale tests)

A past student team had conducted small-scale pressure-impulse tests on 7.5-cm (3-in) dia. samples of both conventional and high-strength filter media and similarly-sized hand-fabricated model filter packs with promising results(7). Consequently, a follow-on team had assembled an intermediate-scale test rig consisting of a vertical column of nominal 250-mm (10-in) ID PVC pipe and a manually-actuated butterfly valve of nominal 10-in diameter. It had a flow cross-sectional area of 0.052 m^2 (0.56 ft^2), a fall distance of 3.2 m (10.6 ft), max. water column height of 4.2 m (13.8 ft), and total height of 7.6 m (25 ft).

Proof-of-concept tests had then been performed by a third, direct-predecessor student team(8) on manufacturer-supplied 203-mm x 203-mm x 149-mm (8-in x 8-in x $5^{7}/_{8}$-in) filters - conventional units and high-strength prototypes; each group consisting of three filters each. Shown in Fig. 2 are plots of the differential pressure with time across a conventional, and a prototype high-strength unit, as measured 9 cm (3.5 in) upstream of the test filter during a pressure-impulse test. The secondary, subsequent peaks resulted from decaying pressure oscillations in the water column above the test filters and exhibit resonant-like periods of approx. 1 s. Very similar periods of post-peak-pressure oscillations were observed for the other intermediate-scale filters tested. This was also the case for the 7.5-cm (3-in) dia. samples of high-strength filter medium investigated earlier(7, 8).

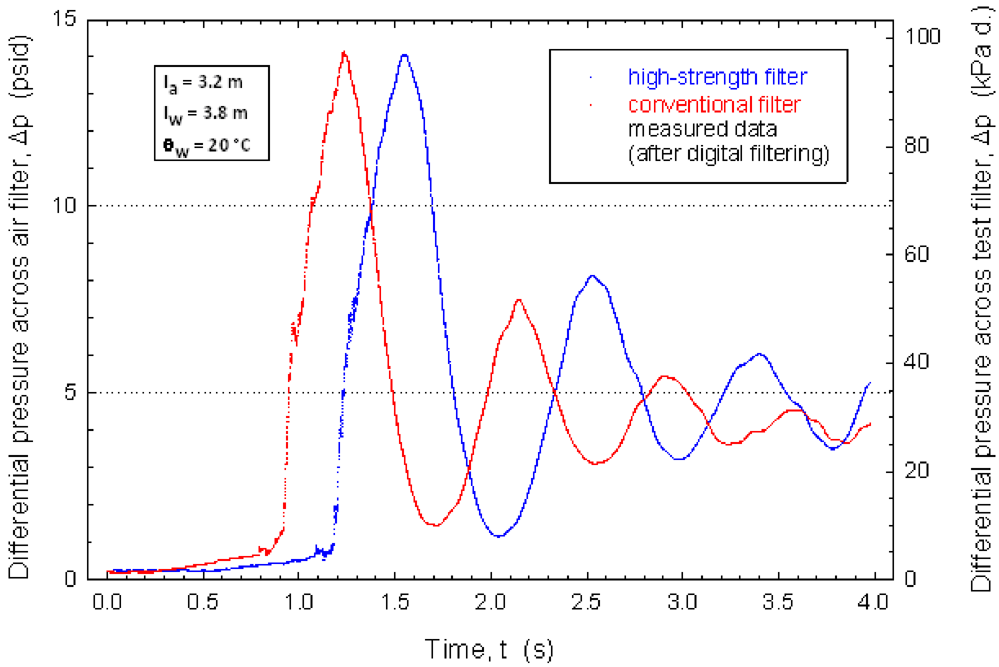

Figure 2: Plots of differential pressure across a 203-mm x 203-mm x 149-mm (8-in x 8-in x $5^{7}/_{8}$-in) conventional, and a prototype, high-strength filter during a pressure-impulse test(8).

For peak filter impulse pressures between 83 and 130 kPa (differential) (12 and 18.5 psid), both pre- and post-test particle penetration values for the three prototype high-strength filters in a dry state were not greater than 0.03%. No visible post-test damage to the filter medium was evident for any of the high-strength prototypes. In comparison, each of the three conventional filters failed catastrophically during tests having peak impulse pressures between 46 and 94 kPa (diff.) (6.6 and 13.6 psid)(8). Thus, no post-test filtration efficiency measurements were performed. Post-peak pressure oscillations (s. Fig. 2) were less pronounced for the three conventional filters. This was attributed to the mode of catastrophic failure which somewhat dampened reflections of the pressure-impulse wave back up through the water column as it drained through the test filter after impact.

The most relevant conclusion to be drawn from the results of the intermediate-scale filter tests was that even a 7.6-m (25-ft) tall test rig may not be high enough to generate failure Δp's of high-strength filters. Disadvantages of an excessive rig height [>4.6 m (15 ft)] include inordinate ceiling height requirements, an expensive support structure, and extra operational-safety and ergonomic considerations. The search began for a means to generate pressure impulses sufficient to determine filter burst strengths, without unduly large water column heights and fall distances. After consideration of some 10 prospective modifications to the falling water column concept, one was recommended as best suited(8). It is based upon augmenting the gravity-driven acceleration of the falling water column, using compressed air above it as a propellent medium. This is intended to allow both the height of the water column and its fall distance to be reduced.

Design alternatives evaluated

From the start of the full-scale rig design project, several options were considered for evaluation. The first involved using nozzles and water at a high pressure to generate free-stream sprays of water within the air inside a duct above the test filter pack to provide a pressure impulse. The drawbacks to this were ensuring that the nozzles covered the entire cross-sectional area with a uniform flow, as well as creating the necessary differential pressure across the test filter with a reasonably practical power input. The estimated cost for this major variation on the falling water column concept was $3,430.66 for a layout with uncertain power requirements.

The two other design options considered, fully represented the falling water column concept. One involved a structure to accommodate a nominal 24-in C-905 PVC pipe of roughly 20 feet in height using a compressed-air actuated, 24-in pinch valve. The primary issues encountered with this was the $55,000 cost of the valve and its massive weight. Additionally, the pinch valve was not an off-the-shelf item and had a quoted delivery time of 5-6 weeks. See Tables A-1 and A-2 for a summary of the estimated material costs for each option and a detailed one for Option 3.

The third design option consisted of a support structure to accommodate a nominal 24-in C-905 PVC pipe which would be also be approx. 20 feet tall, but utilize a 24-in dia. butterfly valve (s. Fig. 3). This was the option chosen. It was selected because the butterfly valve of ductile iron was in stock locally at a discount price and it weighed less than 4.5 kN (1000 lb). Also, the total cost for this alternative was estimated to be approx. $11,000.00.

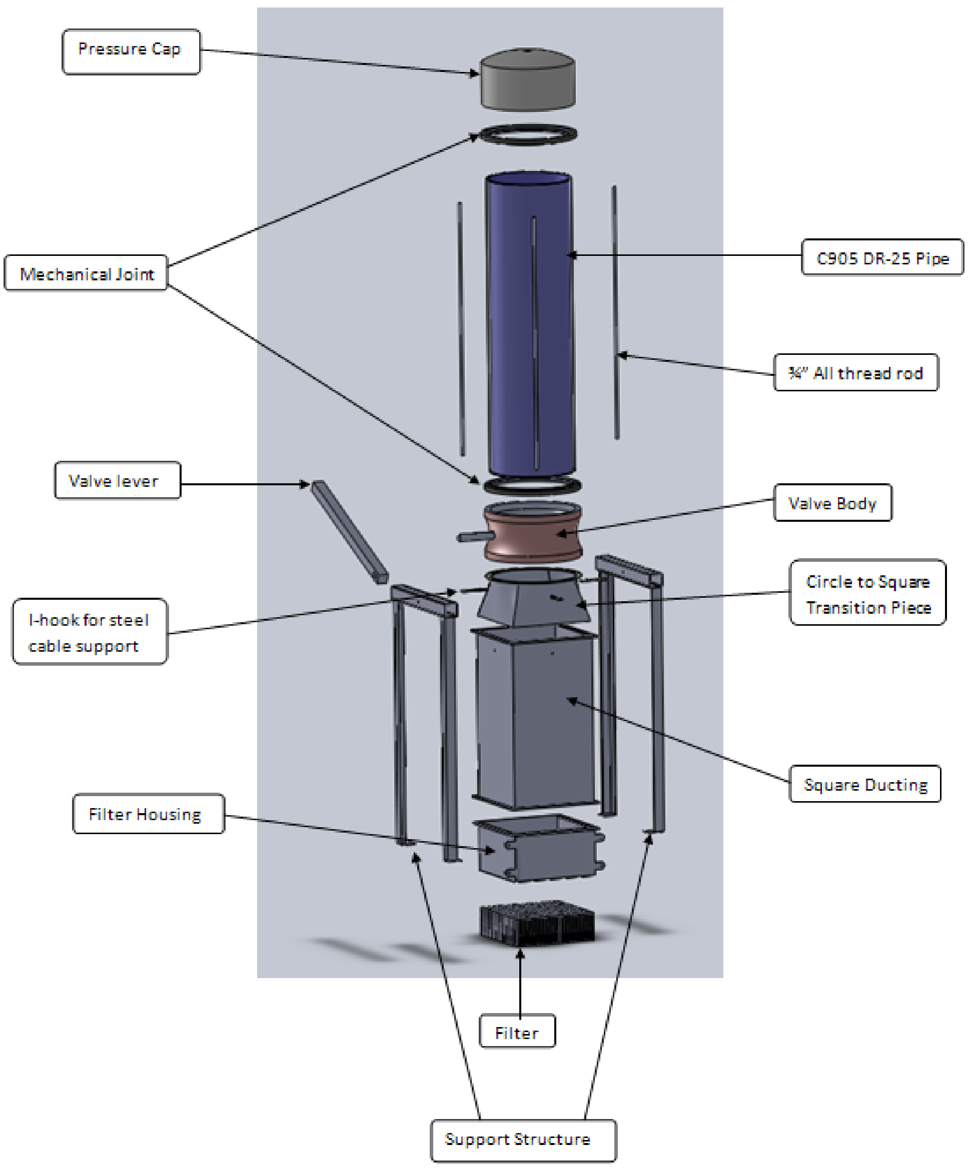

Figure 3: Exploded view of preliminary design of full-scale prototype test rig for qualification testing of high-strength filters.

Project Results

The primary results of this design and fabrication project are summarized in the Appendix. Compiled in Table A-3 are the physical characteristics and the performance specification of the prototype full-scale test rig, together with its utility requirements. A typical example of the results of stress distribution calculations obtained via finite element analysis (FEA) on the structural members of the rig is illustrated in Fig. A-1. Figures A-2 through A-4 show the rig in various stages of completion during the assembly process, in reverse chronological order.

Conclusions

Technical and economic analyses led to the design and realization of a transportable full-scale prototype filter test rig to meet the requirements for conducting the pressure-impulse test needed for qualification of high-strength HEPA filters to proposed Code Section FM of AG-1.

Shakedown testing of the test rig remains to be conducted and operational procedures for it documented. Once rig functionability has been proven, parametric tests on commercial Level I and Level II high-strength filters need to be conducted to find the optimum operating values for water column heights and air-cushion pressures. Determination of minimum required fall distances may also become necessary, with respect to decreasing overall test-rig height, or for the qualification of filters having case geometries other than those for which the rig was initially designed.

Burst strengths for commercial high-strength filters of both Level I and Level II need to be obtained such that proof strength values can be derived from them and specified in Section FM.

The results of the shakedown and parametric testing can also be used to identify which modifications to the rig may be required for realization of the test stand to be located at Edgewood toward use in routine qualification testing. The prototype rig itself would then be so modified and transported to Aberdeen, as initially envisioned.

The implementation of a means to reuse the water for multiple tests is recommended. A water re-cycling system could be expected to consist of a catch basin, a sump, a pump, a filter, and connecting piping. A design and implementation of a data-acquisition system for routine qualification tests will become necessary, building upon the experience gained with the probe, instrumentation, and recording equipment used in the intermediate-scale filter testing. Design of a powered mechanism for valve actuation remains to be addressed.

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PMS Metals, Inc.
New Mexico Bolt and Screw, Inc.

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Appendix

Table A-I: Total estimated material costs for Design Options 1-3.

Design Option	Description	Total Materials Cost ($ US)
1	Water spray from multiple nozzles	3,430.66
2	Falling water column with pinch valve	62,966.26
3	Falling water column with butterfly valve	10,615.90

Table A-II: Summary of estimated material costs for Design Option 3.

Qty.	Description	Part Number	Unit Cost ($ US)	Total ($ US)
1 ea.	24-in butterfly valve, ductile iron	999-0	3780.00	3780.00
20 ft	24-in C-905 PVC DR 25 Pipe	999-9945	1287.60	1287.60
1 ea.	24-in MJ cap w/tap, ductile iron	999-9936	332.64	332.64
4 ea.	24-in PVC Star grip mech. joint	999-9936 (sic)	282.44	1,129.76
30 ft	1/4 x 3 flat bar, steel	150-250	1.93	57.90
20 ft	10 x 3 C-channel, steel	120-1000	15.85	317.00
100 ft	3 x 3 x 1/4 square tubing, steel	175-2500	6.77	677.00
20 ft	3.5 x 3.5 x 1/4 square tubing, steel	175-1800	7.85	157.00
90	2 x 2 x 1/8 square tubing, steel	175-1800 (sic)	3.12	280.80
80	3/4 round bar, steel	155-075	1.21	96.80
misc. items	(compressor, pump, piping, hardware)	-		2,500.00
			Total	10,615.90

Table A-III: Nominal characteristics and utility requirements for prototype full-scale filter test rig.

Parameter	Value
Operating temperature range	20 $\pm$ 5 °C (70 $\pm$ 9 °F)
Pressure impulse, max. differential	280 kPa (40 psid)
Liquid flow, max. (estimated)	2.0 m^3/s (72 ft^3/s)
Liquid column height, max.	3.0 m (10 ft)
Fall distance, max.	1.7 m (5.5 ft)
Valve opening time, max. (estimated)	<800 ms
Valve breakaway torque, max. (estimated)	0.70 kN-m (500 lb-ft)
Static working pressure of high pressure section, max.	1.7 MPa (250 psig)
Accelerant air pressure, max.	350 kPa (50 psig)
Liquid volume capacity, max.	810 l (220 gal)
Gas volume capacity, max.	0.57m^3 (20 ft^3)
Inside diameter of pipe and valve	0.58 m (1.9 ft)
Flow cross-sectional area inside pipe	0.27 m^2 (2.9 ft^2)
Flow cross-sectional area at test filter, max.	0.33 m^2 (3.5 ft^2)
Dry weight, approx.	1.8 $tons_m$ (4000 lb)
Weight at maximum liquid volume capacity, max.	2.7 $tons_m$ (6000 lb)
Power rating of water-pump drive motor, max.	400 W (0.54 hp)
Power rating of air-compressor drive motor, max.	746 W (1.0 hp)

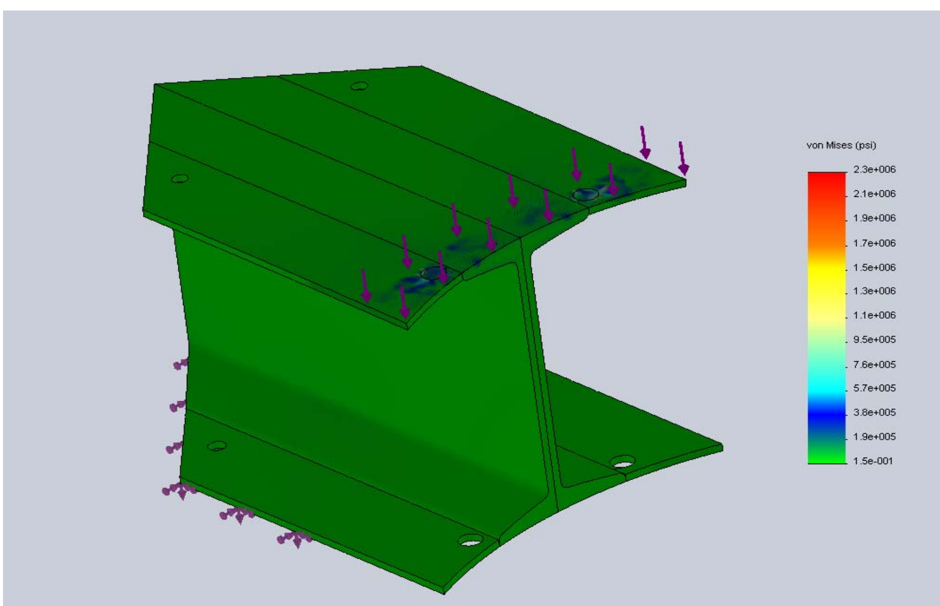

Figure A-1: Stress distribution on top-surface of edge on valve support member at eight-times actual load (typ. one of four).

Figure A-2: Side view of assembled prototype full-scale rig for qualification of 610-mm x 610-mm x 292-mm (12-in x 12-in x $11^{1/}{}_{2}$-in) high-strength filters to pressure impulse test, less test section.

Figure A-3: First assembly of valve and upper pipe-enclosure cage on support structure (with design team).

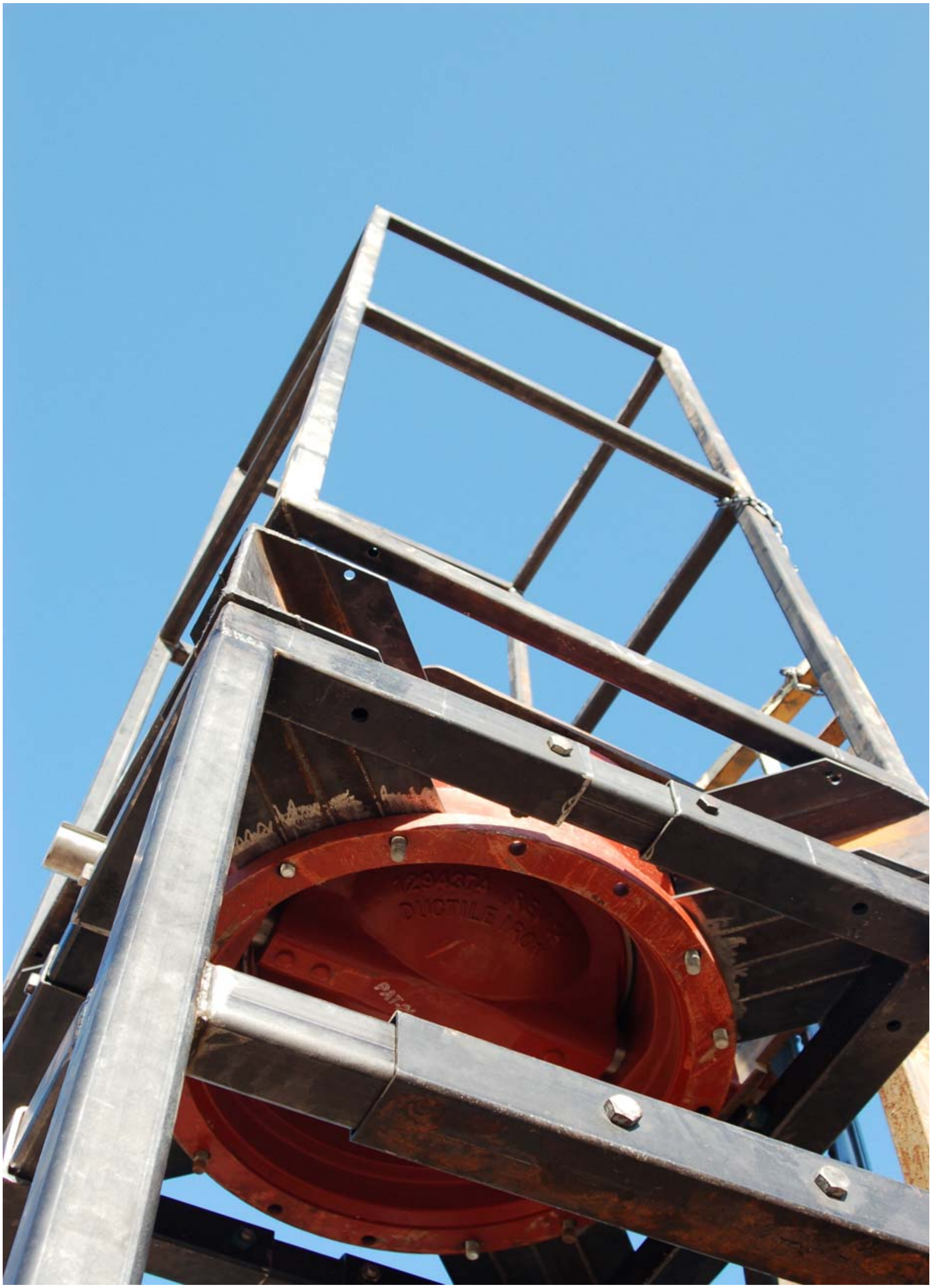

Figure A-4: Bottom view of preliminary assembly of valve support structure, valve, and upper pipe-enclosure cage.