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INTERNAL FLOW MEASUREMENTS OF THE SSME FUEL PREBURNER INJECTOR ELEMENT USING REAL TIME NEUTRON RADIOGRAPHY

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Abstract

Due to observations of unsteady flow in the Space Shuttle Main Engine fuel preburner injector element, several flow studies have been performed. Among them, real time neutron radiography tests were recently completed at the University of Michigan, Phoenix Memorial Laboratory. This technique provided real time images of Mil-C-7024 and Freon-22 flow through an aluminum liquid oxygen post model at three back pressures (0, 150, and 545 psig) and pressure drops up to 1000 psid. Separated flow appeared only while operating at back pressures of 0 and 150 psig. The behavior of separated flow was similar to that observed for water in a 3X acrylic model of the LOX post. On the average, separated flow appeared to reattach near the exit of the post when the ratio of pressure drop to supply pressure was about 0.75.

Introduction

During Pratt & Whitney's ATD HGS (Alternate Turbopump Development Hot Gas System) cold flow testing, several injector element designs were evaluated for their atomization and spray pattern characteristics. Tests on the Space Shuttle Main Engine (SSME) Fuel Preburner Injector Element at certain pressures showed the flow exiting the element behaved in an unsteady manner. Additional testing with an acrylic model showed the flow through the element's internal post oscillated up and down due to the reattachment of separated flow. If such oscillations occurred during SSME operation, they may have contributed to cracks observed in the fuel preburner injector elements. To further investigate these concerns, several internal flow studies on the element's internal post have been undertaken.

In particular, the University of Michigan, Phoenix Memorial Laboratory (PML) recently performed real time neutron radiography (RTNR) tests on a concentric axial flow (CAF) oxidizer element, as requested by the Science & Engineering Directorate and the SSME Program Office of NASA's Marshall Space Flight Center (MSFC). Textron, Inc. provided additional support personnel and test equipment under the existing HGS program. Neutron radiography is used in a wide variety of basic research applications and is particularly useful in studying flow characteristics inside metallic hardware1,2,3,4,5. The technique is similar to X-ray radiography where a beam of radiation is passed through the object of study and the resulting modulated beam forms an image of the object's internal structure. In many cases where X-rays are unsuccessful in providing the desired image, neutrons can be used. For example, images of compounds containing hydrogen atoms inside metallic structures can be produced with neutron radiography because of hydrogen's high absorption coefficient for neutrons and the relatively transparent nature of most metals to neutrons.

PML was able to use neutron radiography to provide a view of the internal flow characteristics within a CAF LOX post. The purposes of the study were (1) to allow a real time view of the flow developing within the LOX post at various operating conditions and (2) to provide an average view of the images and spray pattern. The images produced were recorded on 3/4" video tape. B/W and color enhanced photographs of the images along with plots of average density variations were made at specific conditions.

This paper presents a summary of the technique and facilities involved in the RTNR tests, the experiments performed, and the results obtained. A comparison of these test results with those of other flow tests associated with the study of the fuel preburner injector element is also provided.

RTNR Technique and Facility

Neutron radiography is analogous to x-ray radiography in that a beam of radiation is modulated by an object and that modulated beam is used to form an image of the internal structure of the object. In many cases, x-ray radiography is unable to image phenomena that is of interest to investigators in a wide variety of fields. Images of many of these phenomena can be obtained using neutrons. For example, using neutrons an investigator can obtain images of hydrogenous compounds inside metallic structures. Showing for example, the flow of hydrogenous fuels or fluids inside the oxidizer element.

Figure 1 shows the mass absorption coefficient(relative absorption) of the elements as a function of the atomic number (or the number of electrons). The mass absorption coefficient for photons(x-rays and gamma-rays) is monotone increasing when plotted against increasing atomic number because photons are attenuated by electrons. Neutrons, however, are attenuated by specific nuclear properties and the mass absorption coefficient is not related to atomic number. Figure 1 illustrates this difference. Materials which have a high absorption coefficient for neutrons include hydrogen, boron, lithium, cadmium, and gadolinium while materials which have a low absorption coefficient for neutrons include magnesium, aluminum, iron, titanium, silicon, and zirconium.

In neutron radiography there are three basic methods used to obtain images using neutrons. These are: 1) film neutron radiography-this method converts the attenuated neutron beam into a secondary radiation which is used to expose film; 2) real time neutron radiography (RTNR)-this method converts the neutron beam into a light image which is electronically intensified and viewed by a TV system which can be connected to an image processing system; and 3) transfer film neutron radiography-this method converts the modulated

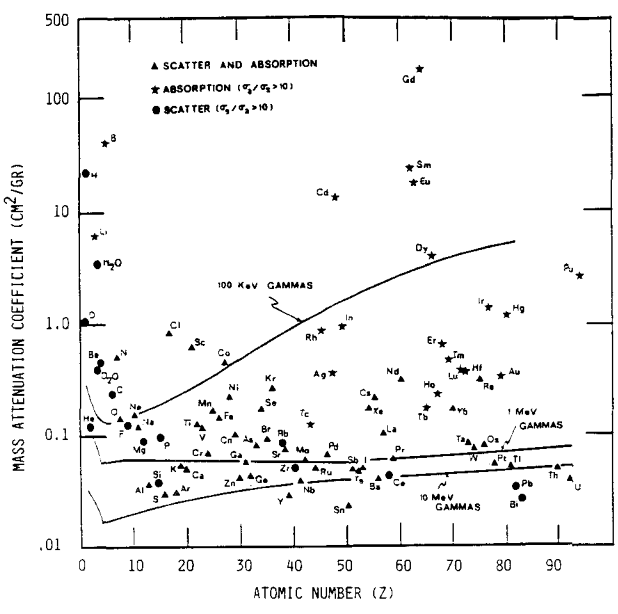

Figure 1. Mass attenuation coefficient for thermal neutrons, 100 KeV gammas, 1 MeV gammas, and 10 MeV gammas as function of atomic number, z.

neutron beam into an induced activation of a screen which is then used to expose the film at another location. At PML we use primarily the first two neutron radiography methods and RTNR was the method chosen for this study.

RTNR converts the attenuated beam of neutrons into a light image which is electronically amplified. At PML various gadolinium oxisylfide screens are used to convert the modulated neutron beam into a light image. This light image is viewed with a TV camera, typically an ER neuvicon. This video image can be input to a computerized image processing and enhancement system for further enhancement and/or measurements, or the video image can be recorded on a video tape for later use. The image is obtained in real time(a new image every 33 milli-seconds) which allows movement and changes to be observed. This is analogous the use of x-rays to study the blood flow in the human heart.

The RTNR facility at PML is located in the Ford Nuclear Reactor facility on the North Campus of the University of Michigan. The thermal neutron source is a two Megawatt reactor reflected on one side with deuterium oxide. A divergent beam of neutrons from the deuterium oxide tank is passed through the object to be radiographed and the attenuated beam is detected by the imaging system. There are two beam ports available for neutron radiography. A vertical beam tube, with a L/D of 340 to 450 and a beam diameter of 2.8 inches, is used primarily for high resolution work using the gadolinium metal screen and film or for high resolution RTNR imaging. The second port is a horizontal beam with a L/D of 50 and a beam diameter of 12 inches. Figure 2 shows a schematic of the horizontal beam port which was used in this project. This beam port is used for large objects and small objects where high resolution is not necessary. Both film and real time neutron radiography is performed using this port.

Currently, two real time imaging systems are in use at PML and both systems were used in this study to allow different views of the post. One consists of an 8" x 8" gadolinium oxisulfide screen mounted in a light tight box, a front surface mirror to reflect the image at right angle to the screen, a f/=0.8 lens, and an EMI magnetically focused image intensifier tube. Figure 3 is a schematic of the complete imaging system using the EMI intensifier. This system was used to provide a view of the complete post, as well as the flow immediately above and below the post. The other image system is a LIXI Neutron Imaging Detector (LIXI NID) manufactured by LIXI Inc., Downers Grove, Illinois6,7. This device uses an input phosphor that is high in gadolinium to generate a light image outside the vacuum envelope of a high gain visible light micro-channel plate image intensifier tube. In order to avoid lateral light spread and degradation of resolution, both the input and output face plates of the intensifier are made of fiber optics which provide intimate physical contact with the gadolinium phosphor. Because the LIXI NID is completely portable and relatively small in size(51mm input diameter), it is easily placed in an area where internal dynamic motion is to be observed. This system was used to provide high resolution, close-up RTNR images of the post. Either system can be viewed by video camera or standard 35 mm camera. When viewed by video camera, the video signal from either of the imaging devices is sent to a Quantex QX-9200 image processing system. This is an IBM 9002 laboratory computer based real time image processing system. A library of several pre-programed image processing routines as well as several custom routines written by the PML staff is available for computerized enhancement and measurements.

Experimental Method

Textron (Walled Lake, Michigan) provided the mechanical spray rig apparatus, the elements, and made modifications as required during the experiments. Textron personnel along with Larry Tanner and George Cox(United Technologies) and Sandy Elam(Marshal Space Flight Center) specified the fluid and experimental variables to be investigated. The RTNR work was performed at the PML RTNR Facility using the horizontal beam port. Imaging was performed using both the EMI imaging system and the LIXI NID imaging system. The real time image was sent to the Quantex QX-9200 image processing system for enhancement and averaging. Both B/W and color images were obtained of the internal spray structure. A real time record was also provided by video taping the real time images and the enhanced images on 3/4 inch video tape. In all cases, an image enhancement technique called mask subtraction was used. In mask subtraction, an image is obtained before the introduction of the fluid to be observed. This mask is then subtracted digitally in the image processor from the real time image of the fluid flow resulting in an image which shows only the internal fluid flow. In the B/W pictures, the darker the image, the thicker the average hydrogen density is at that point.

Mil-C-7024 and Freon-22 were used to simulate LOX, which normally flows through the internal post of the preburner injector element. The flows were studied at three constant back pressures (0, 150, and 545 psig) obtained using pressurized gaseous nitrogen from hydraulic cylinders. The maximum possible pressure drop obtained across the post was 1000 psid. The LOX post structure was made of aluminum, which

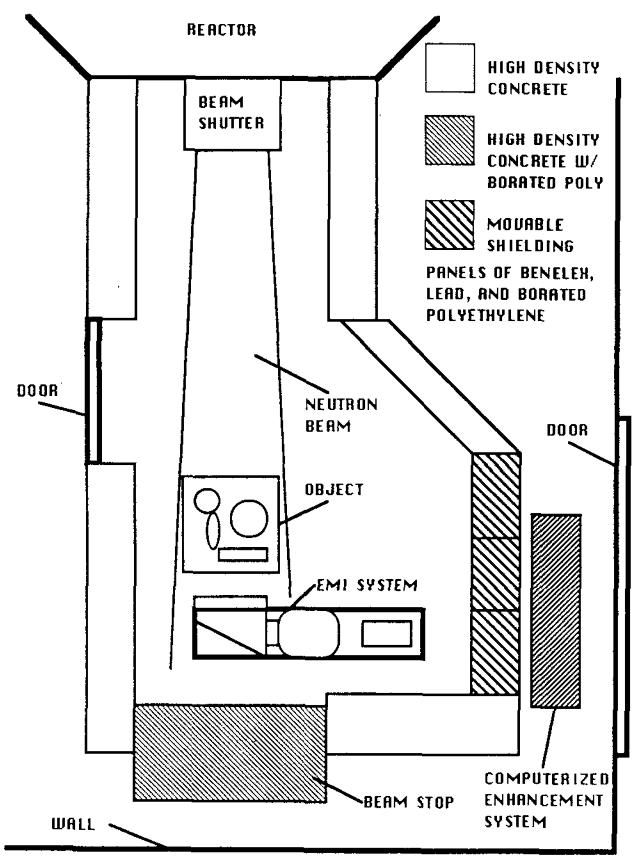

Figure 2 Schematic of the PML RTNR facility and horizontal port.

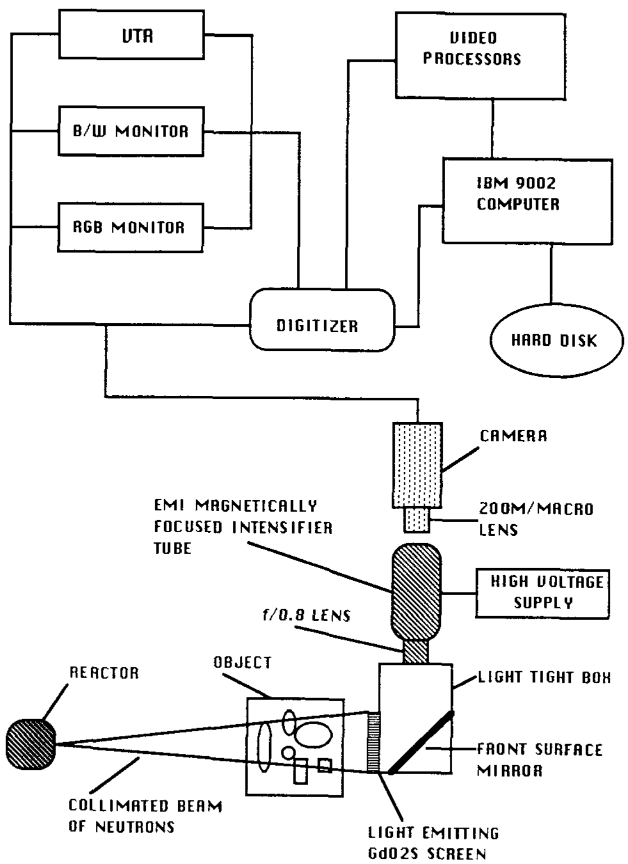

Figure 3. Schematic of the EMI real time imaging system.

has a low absorption coefficient for neutrons. The structure was originally made of stainless steel; however, blurry images resulted because boron, a trace element in stainless steel, readily absorbs neutrons. An enlarged outline of the element structure fabricated by Textron is shown in Figure 4. An annulus surrounds the LOX post to simulate the actual fuel annulus in the preburner injector element, but fuel simulation was not considered in this study.

Table I summarizes the variety of tests performed. Note that Freon-22 was not tested at a back pressure of 0 psig because this fluid easily evaporates at ambient conditions. For a typical test the back pressure was set at the desired value and as the flow began, the resulting real time images, showing the movement and changes of the flow, were observed and recorded on video tape. The pressure drop across the post was increased in increments of 5 psid from 20-50 psid, increments of 10 psid from 50-100 psid, and increments of 25 psid from 100 psid to the maximum values shown in Table I. At each pressure drop the real time images were averaged with an averaging parameter of 128 frames over approximately 30 seconds. Averaged views at specific conditions were then photographed in B/W. Color photos were made of the same views after using the computerized color enhancement techniques.

RTNR TEST RESULTS

Since RTNR essentially detected the flow of hydrogen atoms through the post, the images can be interpreted in terms of hydrogen density. In other words, for the B/W photos and video taped images, the darker the image, the higher the average density of the hydrogen flow. A problem resulted at the elevated back pressures when fluid exiting the post flowed back up into the surrounding annulus. Some fluid

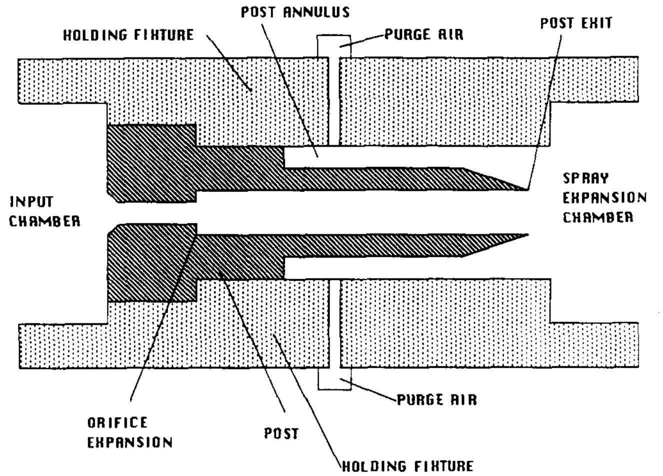

Figure 4. Enlarged outline of the element structure fabricated by Textron, Inc.

became trapped within the surrounding structure and, of course, was detected by the neutron beam. These "leaks" show up in some of the images, but they do not interfere with interpreting the flow behavior inside the LOX post. The problem was partially solved by drilling small holes into the annulus and using a purge to decrease back flow in that area.

Observations of flow behavior were made from the video tapes and photographs. A summary of the observations and their corresponding flow conditions are given in Table II. Generally, the internal flow behavior depended on the fluid, the back pressure, and the pressure drop across the post.

At ambient back pressure, Mil-C-7024 appeared to separate from the LOX post wall at a pressure drop of 35 psid. Figure 5 shows the upper region of the post using the LIXI NID for Mil-C-7024 at a back

Table I. Tests Performed with RTNR

Fluid	Back Pressure (psig)	Image System & Location	Δ P Range
Mil-C-7024	0	LIXI NID - upper post	20 - 600 psid
		LIXI NID - lower post	20 - 600 psid
	150	EMI - complete post	20 - 1000 psid
	545	LIXI NID - upper post	20 - 1000 psid
		LIXI NID - lower post	20 - 1000 psid
		EMI - complete post	20 - 1000 psid
Freon-22	150	LIXI NID - upper post	20 - 500 psid
		EMI - complete post	20 - 500 psid
	545	LIXI NID - upper post	20 - 500 psid
		LIXI NID - lower post	20 - 500 psid

Table II. Summary of KTNR Observations

Fluid	Back Pressure (psig)	Observations
Mil-C-7024	0	35 psid : Flow separation appears, reattaches approx. 0.2" below orifice expansion
		40 psid : Free jet forms, but reattaches 1.4" below expansion
		60 psid : Free jet reattaches approx. 1.5" below expansion
		100+ psid : Free jet exits post without reattaching
	150	425 psid : Flow separation appears & reattaches 0.5" below orifice expansion
		450 psid : Flow reattaches approx. 1.25" below expansion
		475 psid : Flow reattaches approx. 1.5" below expansion
		500 psid : Flow reattaches very close to exit approx. 1.8" below expansion
	545	no separation observed throughout the range of pressure drops
Freon-22	150	125 psid : separation appears and reattaches approx. 0.4" below expansion
		150 psid: reattachment approx. 0.6" below expansion
		200 psid : reattachment approx. 1.0" below expansion
		300 psid : reattachment approx 1.70" below expansioon
		400 psid : reattachment approx 1.75" below expansion
	545	uncertain of separation

pressure of 0 psig and a pressure drop across the post of 20 psid. At these conditions the flow completely fills the upper region of the post. Figure 6 shows the same fluid and back pressure with the pressure drop increased to 35 psid. The flow begins to separate from the post between 0.045" and 0.255" and appears to reattach 0.22" below the orifice expansion. Figure 7 shows the flow at a pressure drop of 40 psid. A free jet formed in the upper portion of the element and remained throughout a pressure drop of 100 psid as shown in figure 8. Figure 9 shows the lower region of the post using the LIXI NID and as can be seen the flow appears to reattach approximately 0.6" above the post exit. The point of flow reattachment continued to move down the post with increasing pressure drop until 100 psid and greater when the jet exited the post without reattaching as shown in Figure 10.

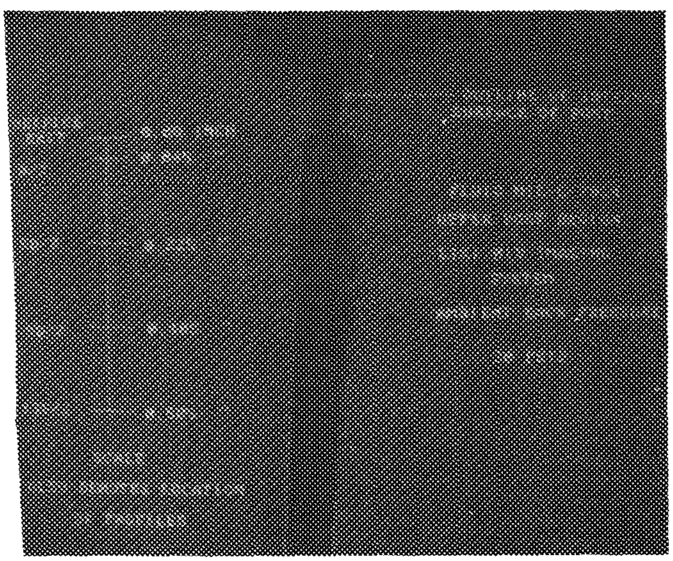

Figure 5. Mil-C-7024 in upper post region. Back Pressure = 0 psig, Delta P = 20 psid. Flow completely fills upper region.

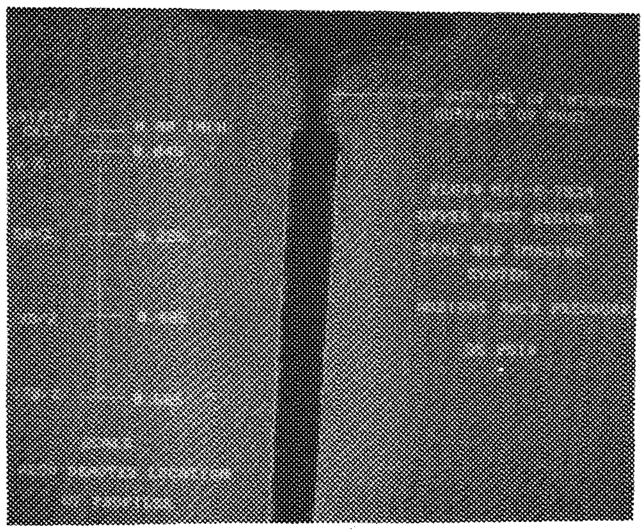

Figure 6. Mil-C-7024 in upper post region. Back Pressure = 0 psig, Delta P = 35 psid. Flow begins to separate from the post between 0.045" and 0.225".

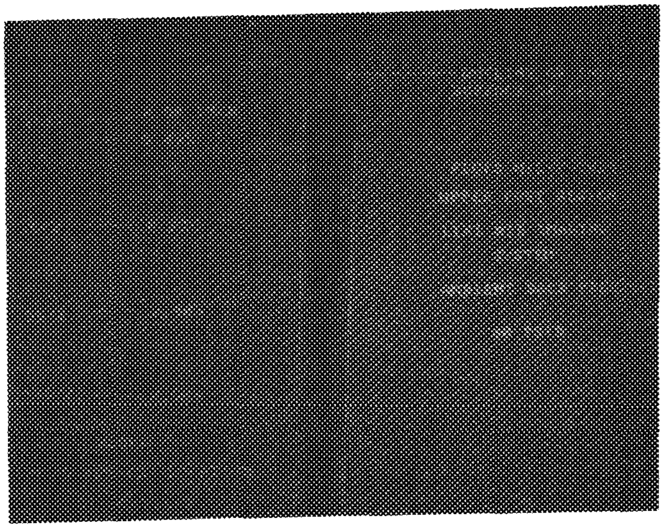

Figure 7. Mil-C-7024 in upper post region. Back Pressure = 0 psig, Delta P = 40 psid. Flow appears completely separated.

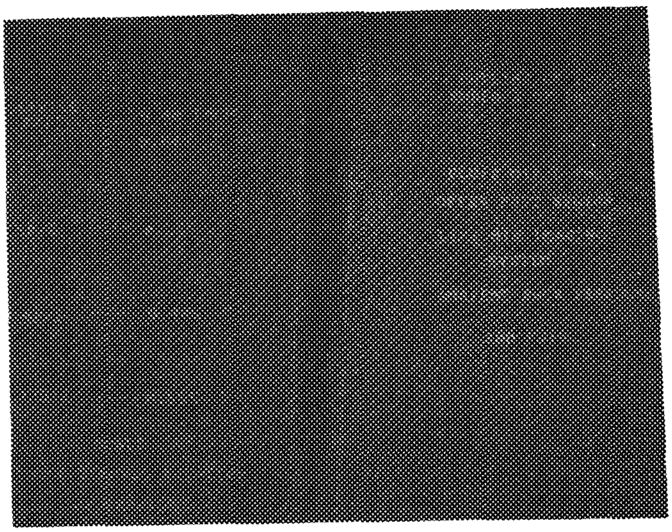

Figure 8. Mil-C-7024 in upper post region. Back Pressure = 0 psig, Delta P = 100 psid. Flow remains completely separated.

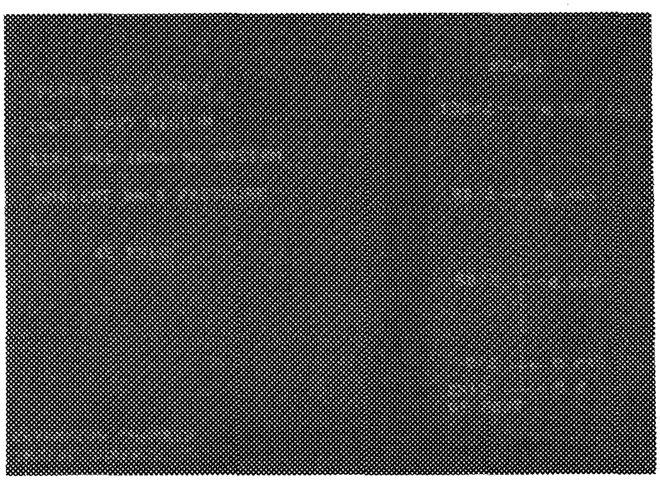

Figure 9. Mil-C-7024 in lower post region. Back Pressure = 0 psig, Delta P = 45 psid. Flow appears to reattach approximately 0.6" above post exit.

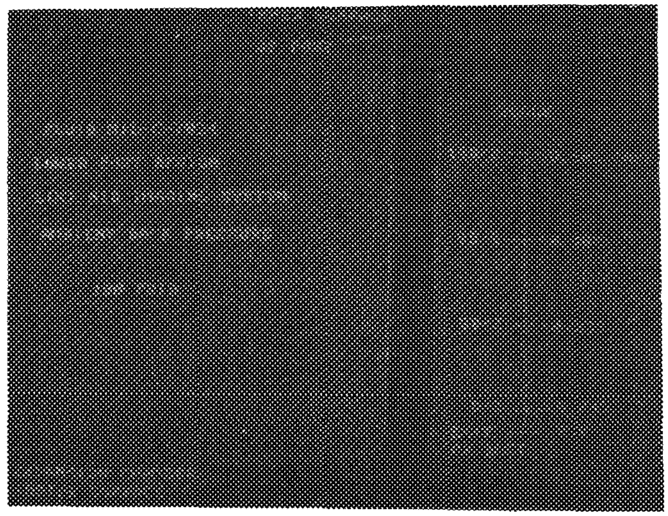

Figure 10. Mil-C-7024 in lower post region. Back Pressure = 0 psig, Delta P = 100 psid. Flow does not appear to reattach before exiting post.

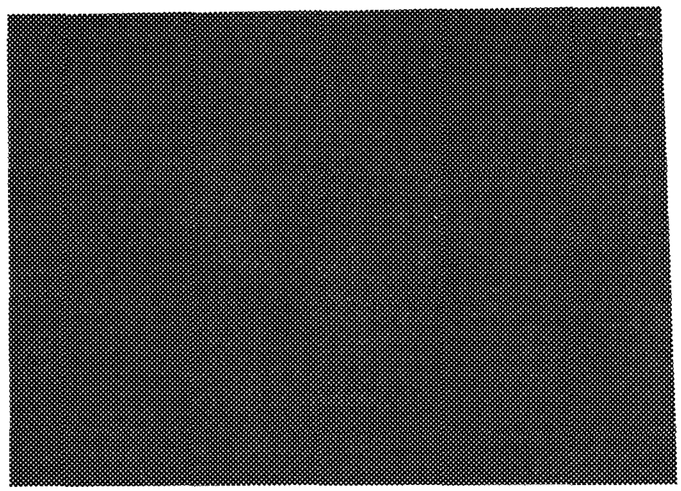

Figure 11. Freon-22 with complete post view. Back Pressure = 150 psig, Delta P = 20 psid. Flow appears to completely fill the post.

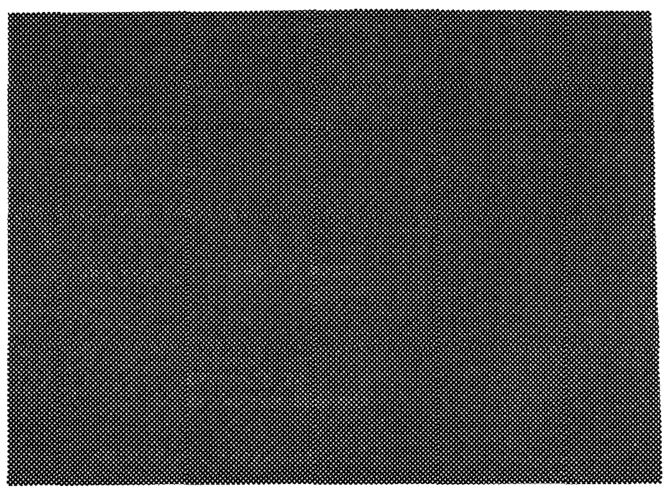

Figure 12. Freon-22 with complete post view. Back pressure = 150 psig, Delta P = 200 psid. Flow appears separated between 0.0" and 1.0" below expansion.

Mil-C-7024 exhibited similar behavior at a back pressure of 150 psig. Separation first appeared at a pressure drop of 425 psid, with reattachment approximately 0.5" below the orifice expansion. At 500 psid, the flow reattached very close to the post exit. At a back pressure of 150 psig and a pressure drop of 20 psid, Freon-22 flow appears to completely fill the post as shown in figure 11 using the EMI imaging system. At the same back pressure, Freon-22 began to separate at 125 psid and reattached approximately 0.4" below the expansion. Figure 12 shows Freon-22 with a back pressure of 150 psig and a pressure drop of 200 psid. Flow appears separated between 0.0" and 1.0" below the expansion. At a pressure drop of 400 psid, flow reattachment was very close to the exit. At a back pressure of 545 psig, neither fluid appeared to separate for any level of pressure drop tested.

Comparison of Flow Work Results

Table III summarizes all the flow work results obtained in the last year concerning the preburner injector element LOX post. Included are the RTNR tests and the water flow tests performed by MSFC's Structures & Dynamics Laboratory. This group performed their tests on a 3X acrylic model of the LOX post at back pressures up to 45 psia. Table III includes the resulting pressure ratios, Delta P/Pc (pressure drop/supply pressure), when separation first occurs near the orifice expansion and when the flow reattachment point reaches the exit. It is interesting to note that the values of Delta P/Pc for reattachment at the exit fall within a narrow range of 0.71-0.80 for all fluids. For data at this condition Delta P/Pc has an average value of 0.75 with a standard deviation of only ±3.6%. Consider the water flow tests when separation never reached the exit while operating at back pressure of 25 psia and greater. If we assume that on the average such a condition will only occur if Delta P/Pc = 0.75, then separation would reach the exit when Delta P = 3 Pb, where Pb is the back pressure. Therefore, at a back pressure of 25 psia, flow separation should near the exit at a Delta P = 75 psid. However, with a maximum supply pressure of 90 psia, the maximum possible Delta P was only 65 psid at a back pressure of 25 psia. Further, for Mil-C-7024 or Freon-22 at a back pressure of 560 psia, separation never appeared within the post. Again, using the above relation, Delta P would have to be 1695 psid before separation reached the exit. The maximum Delta P available was only 1000 psid for Mil-C-7024 and 500 psid for Freon-22. If this relation is generally true, it may be possible to predict when separation near the exit will occur for a given back pressure. Yet, this relation is only based on a small set of experimental results, not on theory. The validity of this relation will be further tested by MSFC's Propulsion Laboratory using a high pressure preburner injector element test rig. This test rig will use liquid nitrogen as the LOX simulate and will achieve pressures up to 2000 psig.

The appearance of flow separation may depend on the fluid's critical conditions. If the fluid is above its critical temperature, separation may not occur when the back pressure is greater than the critical pressure, which may explain the behavior of Mil-C-7024 (P,crit = 315 psia) and Freon-22 (P,crit = 722 psia). However, if the fluid is below its critical temperature, separation may not occur if the back pressure is greater than the vapor pressure. This

Table III. Summary of Flow Work and Relationship Between Pressure Drop and Supply Pressure (Pc)

Fluid	Back Pressure (psia)	When Separation is 1st Observed			When Separation Reaches Exit		
		Δ P (psid)	Pc (psia)	Δ P/Pc	Δ P (psid)	Pc (psia)	Δ P/Pc
Water	15	15	30	.50	50	65	.77
	15	18	33	.54	50	65	.77
	20	20	40	.50	50	70	.71
	25	26	51	.51	n/o	n/o	
	30	39	69	.56	n/o	n/o	
	35	45	80	.56	n/o	n/o	
	40	42	82	.51	n/o	n/o	
	45	44	89	.49	n/o	n/o	
Freon-22	165	125	290	.43	400	565	.71
	560	n/o	n/o		n/o	n/o	
Mil-C-7024	15	35	50	.70	60	75	.80
	165	425	590	.72	500	665	.75
	560	n/o	n/o		n/o	n/o	

n/o : separation not observed

appears to be true for the water flow tests. These theories will also be investigated using the high pressure rig at MSFC.

The values of Delta P/Pc when separation first occurs varied for the different fluids. For water, the average value was 0.52 (with a standard deviation of ±2.6%). The average value for Mil-C-7024 was 0.71. Consider Mil-C-7024 at a back pressure of 560 psia at which flow separation never occurred. If Delta P/Pc must be 0.71, to see initial separation at this back pressure, Delta P should equal 1371 psid, but the maximum value available was only 1000 psid.

The data for Freon-22 only provided one value of Delta P/Pc for initial separation: at 165 psia back pressure, Delta P/Pc = 0.43. If this ratio holds for a back pressure of 560 psia, separation should appear at Delta P = 422 psid. However, separation was uncertain up to 500 psid.

Conclusions

The neutron radiography test series provided an effective technique for imaging the real time internal flow behavior in the CAF LOX post. Results showed flow behavior similar to that previously seen with water in a 3X acrylic LOX post model. Separation may not have appeared in some cases because the pressure drop across the element was not high enough. All the flow work performed so far provides a possible relation between flow separation and operating pressure conditions. Further work will attempt to apply this relation to tests using the MSFC in-house test rig(currently in development) and also to conditions found in the preburners during SSME operation. We will further assess the implication of these results to hardware degradation in the SSME fuel preburners.

As can be seen, neutrons can provide ways to obtain information, not otherwise obtainable, that can be used to develop new and improved technologies and further basic research and science. RTNR can be used to study internal flow and to develop and test new designs and changes before insertion into full scale hardware.

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