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VIBRATION AND COLLAPSE TESTING OF SM-2 FUEL ELEMENTS

JANUARY 1959 TO JANUARY 1960

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January 1959 to January 1960

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ABSTRACT

Experiments were conducted on SM-2 fuel elements to determine (1) the presence of flow-induced fuel plate vibrations, their frequency and amplitude; and (2) verification of the ability of welded fuel elements to resist any tendency towards a flow-induced channel collapse. Test facilities, instrumentation, and procedures are described in detail. Results of tests showed (1) vibrations are practically non-existent in SM-2 welded fuel elements; (2) welded fuel elements will effectively oppose channel collapse; and (3) the addition of combs at the leading and trailing edges of the fuel plates will eliminate any possibility of flow-induced channel collapse at higher than normal flow rates, and insure vibration-free operation.

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1.0 SUMMARY

As part of the SM-2 Fuel Element Structural Test Program (Task 6), experimental tests were conducted on SM-2 fuel elements to ascertain if flow-induced fuel plate vibrations are an inherent operating characteristic. Measuring techniques were developed to determine frequency and amplitude of vibrations. Subsequent investigations were carried out to verify the ability of welded elements to resist flow-induced channel collapse.

Instrumentation for the vibration and collapse tests involved the use of (1) vibration pick-ups mounted on the test element, and connected to an oscilloscope, and (2) velocity probes, connected to a bank of manometers, for measuring water velocities within the coolant channels,

Two types of welded SM-2 fuel elements were used as test specimens during the experiments: a resistance welded fuel element containing solid stainless steel plates, and a TIG welded element containing plates with depleted UO_2 cores.

Test results showed:

1. There was no evidence of significant flow-induced resonant or sustained plate vibrations in the SM-2 fuel elements at water velocities up to 30 fps.
2. Welded fuel elements will effectively resist channel collapse at normal SM-2 flow-rates.
3. The attachment of combs at the leading and trailing edges of the fuel plates will assure vibration-free operation and eliminate flow-induced channel collapse at high flow-rates.

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2.0 TEST FACILITIES

2.1 TEST RIG DESCRIPTION

The test rig assembly for the vibration and collapse tests is shown in Fig. 2-1 and 2-2. Construction details are shown in Fig. 2-3. The prototype element is supported within a Plexiglas tube in accordance with one of the proposed designs to provide the channel to channel flow distribution required for SM-2 fuel elements. Inlet and outlet plenum chambers are provided to stabilize the water flow entering and leaving the rig. The transparent plastic tube was provided to permit visual examination of the test specimen during test runs.

2.2 TEST ELEMENTS

During initial tests, the test element consisted of a resistance-welded fuel element containing solid stainless steel plates. In this element, each plate is welded every 1/2 in. in a straight line along the element. With the exception of the side plate thickness (0.025 in.), the general dimensions are the same as presented in Table 2-1.

The second element tested was TIG welded (Tungsten electrode, inert gas shield), and contained fuel plates with depleted UO_2 cores. There are 16 welds to each fuel plate in this multiplate assembly. They are 1/2 in. in length and spaced 3 in. apart. The weld pattern is staggered, a weld on one edge of a fuel plate occurring at the midpoint between welds on the opposite edge. The same staggered pattern is used between adjacent fuel plates. Dimensional data on this element is given in Table 2-1.

TABLE 2-1
DIMENSIONS OF SM-2 TIG WELDED FUEL ELEMENTS

Overall Length (incl. end fixture) - - - - -	26-1/2 in.
Fuel Plate Length - - - - -	23-1/2 in.
Fuel Plate Width - - - - -	2.87 in.
Side Plate Width - - - - -	2.86 in.
Fuel Plate Thickness - - - - -	0.040 in.
Side Plate Thickness - - - - -	0.040 in.
Fuel Length - - - - -	22 in.
Fuel Width - - - - -	2.67 in.
Number of Fuel Plates - - - - -	18
Fuel Plate Spacing - - - - -	0.163 in.
Coolant Channel Width - - - - -	0.123 in.

2.3 TEST INSTRUMENTATION

In determining appropriate instrumentation for the vibration and collapse tests, particular emphasis was placed on the selection of suitable sensing devices for obtaining the required information from the test specimen.

A survey was made of various types of devices for detecting the fuel plate vibrations. A linear variable differential transformer, containing a movable core, and equipped with a pick-up probe, was found to be most suitable for this application.

In operation, a low voltage signal (3-6v, 2-20kc) from a signal generator is fed to the transformer input terminals (primary winding), and the output voltages from the secondary winding are indicated on an oscilloscope. When mechanical vibrations are picked up by the probe, corresponding movements of the core will in turn result in proportional changes in the transformer output voltages observed on the oscilloscope.

The vibration pick-ups were mechanically attached to several fuel plates at different axial locations, as shown in Fig. 2-4 and 2-5. Six of these pick-ups were used in the tests conducted on the first element, Fig. 2-4, (resistance-welded) but, due to physical limitations presented by the UO_2 cores, only four vibration pick-ups could be mounted on the second element, Fig. 2-5, (TIG welded). Figures 2-6 and 2-7 provide exterior views of the four pick-ups mounted in position on the second test specimen. Figure 2-8 shows the pick-up probe mechanically attached to an inner fuel plate. In Fig. 2-8 the smaller cylinder, seen in the innermost channel crossed by the probe, is the actual link to the movable core. The larger cylinder, seen in the outer channels, is a protective sheath installed to prevent flow forces from distorting the active probe.

The vibration pick-up cabling is shown in Fig. 2-9. The various output voltages were selectively routed to the oscilloscope by means of a channel selector switch for individual examination of each probe.

Following installation of the pick-ups, the transformers were calibrated (see Appendix 5.1.2) to assure accuracy in measurements. For the initial tests a 20 kc, 6v signal was used, but subsequently, because moisture (due to immersion) in the windings and connecting terminals resulting in electrical leakage, the signal frequency was reduced to 2 kc at 3 volts. Potting the terminals, cable shielding, and other corrective measures were taken to eliminate electrical leakage, stray fields, etc.

The pitot-static sensing devices for detecting flow velocities were specifically designed and constructed by the Alco Mechanical Laboratory for these test procedures. Seventeen static pressure probes and 17 total pressure probes were mounted in two rakes (see Fig. 2-10) at the exit end of the

test element. A total pressure and a static pressure probe were installed in each coolant channel, located 1/4 in. upstream of the exit of the channel. The differential pressure information obtained from these probes indicated the individual channel flow velocities on a bank of manometers.

In collapse testing, the pitot-static probes were used to detect channel collapse. An abrupt decrease in velocity through any channel accompanied by a slight increase in adjacent channel velocities, indicated a condition of collapse in the low velocity channel.

The principal measuring devices used in the vibration and collapse tests were assembled, as shown in Fig. 2-11. These instruments included the following: an oscilloscope (Memoscope), the signal generator, a vacuum tube voltmeter, a rack of manometers, a temperature indicator, and a channel selector switch. In Fig. 2-11 the element in position for testing is visible in the background.

The Memoscope is a special type of oscilloscope particularly adaptable to the examination or photographing of the pick-up transformer output wave form. A single sweep image can be retained for several minutes on this instrument, thus allowing the operator to determine the value of any given image prior to photographing. Photographs of the wave form were taken with a special oscilloscope camera using Polaroid film.

The vacuum tube voltmeter was used to monitor the supply voltage from the generator to the pick-up transformer primary windings. The signal generator covers the frequency range from 0 to 20 Kc, and has an adjustable output voltage.

The manometer rack contains 17 "U" tubes for simultaneous monitoring of individual channel velocity pressures.

Figure 2-12 shows the manner in which the instruments used for the vibration tests were interconnected.

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Fig. 2-1 Vibration Test Rig and Element - Side View

Fig. 2-2 Vibration Test Rig and Element - End View

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SECTION A-A

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SKETCHES

1	1/2" DIA. CAPSCREW	2	1/2" DIA. CAPSCREW
3	1/2" DIA. CAPSCREW	4	1/2" DIA. CAPSCREW
5	1/2" DIA. CAPSCREW	6	1/2" DIA. CAPSCREW
7	1/2" DIA. CAPSCREW	8	1/2" DIA. CAPSCREW
9	1/2" DIA. CAPSCREW	10	1/2" DIA. CAPSCREW
11	1/2" DIA. CAPSCREW	12	1/2" DIA. CAPSCREW
13	1/2" DIA. CAPSCREW	14	1/2" DIA. CAPSCREW
15	1/2" DIA. CAPSCREW	16	1/2" DIA. CAPSCREW
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19	1/2" DIA. CAPSCREW	20	1/2" DIA. CAPSCREW
21	1/2" DIA. CAPSCREW	22	1/2" DIA. CAPSCREW
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FIG. 2 - 4
VIBRATION-PICK UP LOCATION
ON RESISTANCE WELDED ELEMENT

FIG. 2-5

LOCATION OF VIBRATION PICK-UP PROBE ATTACHMENT TO FUEL PLATES.
(TIG WELDED ELEMENT)

Fig. 2-6 Instrumented TIG Welded Element for Vibration Test

Fig. 2-7 Vibration Pick-Up Mounted on Inlet End of Element

Fig. 2-8 Element End View Showing Vibration Pick-Up and Probe

FIG. 2-9

METHOD OF BRINGING PICK-UP WIRES OUT OF RIG.

Fig. 2-10 Static and Total Pressure Probe Rakes

Fig. 2-11 Instrumentation, Test Rig, and Element, in Test Set-Up

FIG. 2-12 INTERCONNECTING WIRING OF
INSTRUMENTS FOR VIBRATION
TESTS.

3.0 VIBRATION TESTS

3.1 INTRODUCTION

As part of the SM-2 Fuel Element Structural Test Program (Task 6), one requirement consisted of experimentally determining the presence of flow-induced fuel plate vibrations, their frequency and amplitude. The requirement was based on the known existence of factors within the element conducive to formation of resonant or sustained vibrations. Such oscillatory plate deflections would, if of sufficient magnitude, present a recognizable condition of potential plate failure within the element.

The initial steps in the vibration test program involved (1) the development of an appropriate test procedure, (2) an examination of the test instrumentation requirements, and (3) the fabrication, procurement, and assembling of prescribed test facilities, including the test rig, instruments, hydraulic loop, and the test specimens.

To derive the required vibration data, the testing process had to include provisions for simulating all the vibration productive factors normally present within a typical fuel element. Consequently, to obtain these conditions the requirements dictated the use of prototype test specimens, and means for simulating equivalent forces (fluid velocity and distribution).

In addition, it was necessary that the instrumentation employed measure amplitudes of vibration as low as 0.001 in. or as high as 0.20 in. at frequencies from 0 to 2000 cps, with a minimum of flow disturbance and increase to the mass of the plate.

3.2 DISCUSSION OF TESTS

Following installation of instrumentation for vibration testing, preliminary trial runs were conducted to assure (1) satisfactory operation of the hydraulic loop through the test rig, (2) ability to simultaneously monitor all fuel plate channel velocities on the manometer rack over a wide range of up to 150% of design, and (3) proper adjustment and calibration of the vibration indicating instruments.

The test specimen under examination during the initial test was a resistance-welded, solid stainless steel plate element. Vibration pick-ups were mounted on the element (shown in Fig. 2-4) after being calibrated first in air and then while immersed in water.

The signal generator was adjusted to provide a 20 kc signal at 5.5 to 6.5 volts to the primary of the pick-up transformers for the test observations.

Observations were made at loop flow rates of 180, 270, 360, 450, 540, and 630 gpm (corresponding to 10, 15, 20, 25, 30 and 35 fps channel velocities). It was found that during the immersed calibration of the transformers, the connecting leads of four of the six transformers had shorted out. However, in order that the performance of the two remaining transformers might be observed, the testing was continued. These units performed satisfactorily for three flow rates but prior to reaching 450 gpm they also shorted out. Data for the three flows tested is given in Table 3-1.

TABLE 3-1
VIBRATION TEST MEASUREMENTS ON FIRST SPECIMEN AT
180, 270, AND 360 GPM

PICKUP NO.	1	1	1	3	3	3
FLOW RATE gpm	180	270	360	180	270	360
FREQUENCY cps.	4	Unsteady	0	0	0	2
AMPLITUDE ΔV .	.01	.03	0	0	0	.01
DEFLECTION in.	.0005	.001	0	0	0	.0007

The rig was then disassembled and the pick-up leads repaired. During the repair period, fabrication difficulties caused the resistance welding technique to be dropped from the SM-2 fuel element assembly program and the TIG welded element became the reference design. For this reason, further testing of the resistance welded element was discontinued and a new element, TIG welded, with fuel plates containing a depleted UO_2 core, was used for all future testing.

Due to the presence of UO_2 in the fuel plates, vibration instruments could no longer be located at various locations along the length of the element but rather were restricted to within 1/4 in. of each end of the fuel plates (in the solid steel "picture frame" region of the plate) so as not to penetrate the core (see Fig. 2-5).

Prior to testing the second element, the vibration pick-ups were again calibrated. It was found that although the abrupt shorting out of the wiring had been eliminated by the repairs, a drift of the calibration occurred after the pick-ups had been immersed in water for a period of time. This difficulty was overcome by reducing the carrier frequency from 20 to 2 kc.

During one set of tests, in which the velocity flow rates were maintained at 0, 200, 400, and 600 gpm, the Memoscope traces obtained from each transformer were photographically recorded for further study. These photos, taken with the scope sweep time adjusted to 0.01 sec/div. are shown in Fig. 3-1, 3-2, 3-3, and 3-4. Another set of photographs were taken (with a scope sweep time of 0.005 sec/div) of the four transformer output voltages, at a flow rate of 600 gpm (Fig. 3-5). An examination of the recorded information substantiates previous observations that sustained or resonant vibrations were not being generated. The significant region of the photographs is the upper surface of the shaded area. The shaded area is caused by the 2 kc carrier frequency being projected in a relatively slow sweep time. The height of the shaded area is proportional to the output voltage of the pick-up and thus to plate position. Therefore, any movement of the plate would appear as a change in the height of the shaded area.

In all the Memoscope traces a ripple can be seen at the top of the shaded area. The period of the ripple is 0.016 sec (1.6 divisions in Fig. 3-1 through 3-4 and 3.2 divisions in Fig. 3-5). This corresponds to a frequency of $1/0.016$ or 60 cycles and is caused by a stray 60 cycle voltage leaking into the system from some external source.

Since the Memoscope becomes cloudy and loses image retention with time, several of the photographs are not clear, especially the 400 and 600 gpm traces of Fig. 3-2. This was entirely due to a time lapse before taking the picture and is in no way connected with plate vibrations.

An examination of the photographs shows no indication of plate vibration. Figures 3-1 through 3-4 would show vibrations having frequencies between 10 and 100 cps and Fig. 3-5 would show frequencies up to 200 cps. Higher frequencies (up to 2000 cps) were investigated with the same results but no photographs were taken.

One further observation can be made from the photographs. It will be noted that the height of the trace decreases in all cases as the flow increases. This signifies a plate deflection of increasing magnitude with increased flow. This plate deflection has been plotted as a function of flow rate in Fig. 3-6, using the calibration curve for each transformer given in Fig. 5-3. This plot shows that plate 13 (curves 2 and 5) had a deflection proportional to the flow rate while plates 9 and 6 (curves 3 and 4) had a sudden increase in deflection between 200 and 400 gpm flow rates. Two possible reasons could account for this sudden increase: (1) an instrument malfunction or (2) an unstable condition at the ends of the plates resulting in a partial channel collapse. If the latter is the case, installing combs at the leading and trailing edges of the plates (which has since been done to prevent collapse) would eliminate this condition. Combs will also eliminate low magnitude movement of plate 13. As outlined in section 4.0-Collapse Tests, a channel collapse

occurred during vibration testing of the resistance welded element due to accidental fuel plate distortion caused by instrumentation probes. Therefore, to prevent a recurrence of conflicting influences, the vibration and collapse tests were run separately on the TIG welded element.

3.3 CONCLUSIONS AND RECOMMENDATIONS

Based on results of the vibration experiments, it is concluded that although some of the conditions for the generation of resonant vibrations are an integral part of any reactor, the inherent existence of vibration productive forces of sufficient magnitude to produce sustained vibrations is not a reality in the SM-2. These deductions were derived from test conditions which exceeded design requirements by a considerable margin. It can be safely assumed that the fuel plate design and rigidity of construction were deterrents to the formation of resonant vibrations.

The observance of slight, random, vibration-like traces in the memoscope pattern indicated only the presence of stray electrical fields and therefore carried no significance.

Attachment of combs at the leading and trailing edges of the element as recommended in section 4.0 - Collapse Tests, would provide additional assurance of freedom from vibrations and random plate deflections.

Fig. 3-1 Memoscope Traces, #2 Transformer, 0, 200, 400, 600 GPM

Fig. 3-2 Memoscope Traces, #3 Transformer, 0, 200, 400, 600 GPM

Fig. 3-3 Memoscope Traces, #4 Transformer, 0, 200, 400, 600 GPM

Fig. 3-4 Memoscope Traces, #5 Transformer, 0, 200, 400, 600 GPM

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Fig. 3-5 Memoscope Traces, All Transformers, at 600 GPM

FIG.3-6

PLATE DEFLECTION VS. RATE OF FLOW
(TIG WELDED FUEL ELEMENT)

CURVE 2-PLATE 13, INLET END
CURVE 3-PLATE 9, INLET END
CURVE 4-PLATE 6, OUTLET END
CURVE 5-PLATE 13, OUTLET END

4.0 COLLAPSE TESTS

4.1 INTRODUCTION

Another requirement of the SM-2 Structural Test Program was to test the mechanical stability of welded fuel element for resistance to flow-induced strains which eventually can cause a channel to collapse.

To obtain data, part of the instrumentation employed in the vibration tests, the same rig, and the two test specimens, were diverted to these tests. The pitot-static instrumentation previously described was utilized to observe the status of the various fuel plate channels as the velocity flow-rate was varied over a wide range (up to 174% of design). Evidence of channel failure or collapse would immediately be reflected by the manometer readings. An abrupt decrease in any of the channel velocity levels, accompanied by slight increases in adjacent channel velocities, would denote the existence of a collapsed channel. This condition normally occurs near the leading edges of the plates.

Efforts were made to conduct collapse tests in conjunction with the vibration study but due to difficulties encountered, as explained in Section 3.2, testing was carried out separately.

Additional information for the collapse testing was derived from an examination of fuel plate deflections before and after each operation of the hydraulic loop. Dimensional measurements taken from each channel assisted in determining results of the experiments.

4.2 DISCUSSION OF TESTS

The first fuel element subjected to collapse testing was a resistance-welded, solid stainless steel unit. Velocity measuring probes in each of the 17 channels (labeled "A" through "Q" for identification purposes) were piped to individual "U" tube manometers. In this manner, the condition of all 17 channels could be monitored simultaneously while varying the flow rate.

Table 4-1 shows the tabulated data recorded during one of the early test runs on the resistance-welded element. As will be noted, the total loop flow was increased in 90 gpm increments from 180 to 630 gpm, (channel velocity increased in steps of 5 fps). Examination of Table 4-1 reveals a normal step-up in velocity pressure up to the maximum 630 gpm flow in all channels except "L" and "O". In channel "O" the failure to obtain a reading at 630 gpm resulted from a disconnected instrument line. However, in channel "L" the abrupt decrease in pressure recorded at 630 gpm, accompanied by slight increases in adjacent channel pressures, signified a condition of collapse in that channel. A subsequent examination of the element to determine the cause revealed that one of the "L" channel plates had been distorted beyond the dimensional tolerance during the installation of pick-ups for the vibration testing experiments.

TABLE 4-1 VELOCITY PRESSURES TAKEN ON FIRST SPECIMEN

Nom. Channel Velocity ft/sec	Flow Increasing					
	10	15	20	25	30	35
Total Loop Flow - GPM	180	270	360	450	540	630
Channel Letter	Velocity Pressure - Inches Hg.					
A	1.30	2.50	4.35	6.50	8.25	11.20
B	1.50	3.00	5.45	8.20	10.10	13.50
C	1.50	3.10	5.70	8.70	11.35	15.35
D	1.55	3.10	5.70	8.75	11.55	15.60
E	1.70	3.40	6.50	9.55	12.60	17.00
F	1.60	3.40	6.10	9.30	12.25	16.60
G	1.70	3.30	6.00	9.10	12.10	16.20
H	1.70	3.30	6.00	9.00	12.00	16.10
I	1.50	3.10	5.60	8.40	10.95	14.60
J	1.70	3.25	5.95	8.95	11.75	15.90
K	1.70	3.30	6.00	9.25	12.25	16.60
L	1.70	3.30	5.80	8.70	11.45	9.55
M	1.75	3.40	6.15	9.60	12.80	17.40
N	1.70	3.30	5.90	9.00	11.90	15.90
O	1.65	3.25	6.10	9.10	11.85	-
P	1.60	2.95	5.65	8.60	10.85	14.0
Q	1.50	2.80	5.25	7.80	9.75	12.10
ΔP_x^*	4.6	8.6	15.0	21.85	28.20	37.4
ΔP_y^*	4.6	8.6	15.0	21.85	28.0	37.2
Temp.	-	-	-	112.5	125+	125+

* ΔP_x & ΔP_y are static pressure differentials across outer fuel plates.

Nominal channel height for the SM-2 element is 0.123 in. with a tolerance of plus or minus 0.006 in. giving a minimum allowable height of 0.117 in. Table 4-2 gives channel height measurements of the resistance welded element after the vibration pick-ups were installed but prior to testing. It can be seen that channel "L" measured 0.111 in. high 3-1/2 in. in from the end of the element. This is 0.006 in. below the allowable minimum and obviously contributed to the collapse of the channel.

TABLE 4-2
DIMENSIONS OF RESISTANCE WELDED ELEMENT,
BEFORE AND AFTER VIBRATION AND COLLAPSE TESTING

Measurement Location*	3-1/2"		10"		17"		23-1/2"	
	Before	After	Before	After	Before	After	Before	After
Channel Letter	Channel Height (Mils)							
A	129	125	126	121	127	121	127	1225
B	123	116	131	119	128	116	1285	126
C	1225	1225	123	1275	1235	129	123	123
D	126	1235	127	124	129	1225	127	125
E	127	1265	125	125	1255	126	123	123
F	124	123	125	118	126	118	1245	123
G	123	123	125	131	125	1295	120	117
H	1255	124	126	122	1275	1255	126	123
I	125	123	1295	1275	124	1225	130	135
J	122	118	124	1175	125	119	126	121
K	131	131	1275	129	130	1305	1225	123
L	1205	1195	122	121	1225	121	123	1205
M	128	1275	128	1275	129	128	1285	-
N	111	1075	122	1165	1205	1175	117	115
O	133	124	128	129	1305	1285	132	1245
P	127	124	125	123	126	122	121	113
Q	120	114	127	120	126	120	126	124

* Locations are determined from end of element. Heights measured at channel centerline.

For the next series of collapse tests, a second element was mounted in the test rig and the instrumentation reconnected. This was a TIG welded specimen with annealed fuel plates containing a depleted UO_2 core.

Before starting a test run, the height of each channel was measured at four specified points along the length of the element. At the conclusion of the test the measurements were repeated in the same manner. Table 4-3 lists the "before" and "after" dimensions tabulated for a test run on the second element. An examination of Table 4-3 will show that channel "F" received special consideration in the measurement analysis, following the completion of the test run during which this channel collapsed. From the data it can be seen that no permanent distortion of the plates resulted from the collapse.

The manometer readings taken during the above test are presented in Table 4-4. It can be seen that when the flow rate was increased to 530 gpm, velocity pressure deficiencies developed in channels A, F, and Q. However, the low flow at the outer channels (A and Q) is considered of no consequence since the outer fuel plates were subjected to pressure differentials as great as 10 times normal. This high differential was caused by an oversight in rig design which resulted in full loop stagnation pressure being applied to the exterior of the element while the interior felt only static pressure. Values of the pressure differential across the outer fuel plates are given in Table 4-4. In channel "F", a true condition of collapse is evident by the drop in velocity pressure, accompanied by slight increases in adjacent channels. A plot of channel velocities at 540 gpm element flow (Fig. 4-1) shows the collapsed channel to have the highest velocity in the element prior to the collapse. A plot of collapsed channel velocity versus average element flow velocity is given in Fig. 4-2. The velocity of the adjacent channel is presented to show its velocity increase resulting from the collapse. Dimensional measurements taken on the collapsed channel before subjecting it to the test proved it to be well within the prescribed tolerance, although slightly below the average.

The next step in the experiments consisted of a study to determine the probable beneficial effects to be derived from the attachment of a comb at the entrance to the element (see Fig. 4-3). Following installation of the comb, test runs were resumed with results as shown in Tables 4-5 and 4-6. No indications of pending or total collapse at the high flow-rates were observed during this series of tests. In addition, an improvement in the flow distribution to outer channel "A" can be seen. A change in the "Q" channel velocity pressures, at 540 and 630 gpm, can also be detected, but to a lesser degree.

TABLE 4-3
CHANNEL DIMENSIONS, SECOND ELEMENT, BEFORE AND AFTER
TEST RUN (WITHOUT COMB ATTACHMENT)

Measurement Location*	2-1/8"		10"		17"		24-7/8"	
	Before	After	Before	After	Before	After	Before	After
Channel Letter	Channel Height (Mils)							
A	125	113	124.5	100	124	-	123	-
B	131	133	124	113	118	123	128.5	135
C	126	129	129	122	130	123	127	122
D	130	134	124	127	123	127	129	134
E	133	133	126	127	127	129	132.5	133
F	126	See Below	118		118		129	
G	127.5	128	132	133	131	131	129	131
H	133	133	122.5	124	126	128	124.5	129
I	136	135	130	131	123	125	131.5	135
J	133.5	128	130	121	132	124	134	141
K	131	133	130	132	132.5	132	132	126
L	129	127	123	121	122	117	128	112
M	133	135	128.5	132	129.5	137.5	134	153.5
N	132	134	117.5	119	118.5	119	126	123
O	134	136	132	133	131	130	132.5	136
P	124.5	127	125	109	122	121	114	114
Q	128	131	124	100	124.5	-	127	-

Measurements in Channel F After Test Run

Measurement Location*	2-1/8"	3"	4"	5"	6"	7"	8"	9"	10"	11"	12"	13"	14"	15"	16"	17"
	128	129	122	119	121	121	119	118	119	121	120	119	119	121	121	121
Measurement Location*	18"	19"	20"	21"	22"	23"	24"	24-7/8"								
	121	121	124	125	131	130	125	135								

* Locations are determined from end of element. Heights measured at channel centerline.

TABLE 4-4
VELOCITY PRESSURES BEFORE INSTALLATION OF COMB

Nom. Channel Velocity ft/sec	10	15	20	25	30	35
Total Loop Flow - GPM	180	270	360	450	540	630
Channel Letter	Velocity Pressure - inches Hg.					
A	1.8	4.0	6.9	8.2	7.8	3.25
B	1.55	3.35	5.4	6.9	8.75	10.45
C	1.65	3.7	6.0	8.5	11.8	15.65
D	1.9	4.2	7.05	9.95	14.45	17.75
E	1.75	3.9	6.4	8.9	12.2	22.7
F	1.85	4.15	7.05	10.15	15.25	6.95
G	1.65	3.55	5.7	7.5	8.85	18.85
H	1.75	3.95	6.7	9.6	14.25	18.4
I	1.85	3.9	6.4	8.55	11.75	15.4
J	1.8	3.8	6.4	8.8	12.4	16.4
K	1.85	3.65	6.65	9.8	13.4	17.0
L	1.75	3.8	6.4	9.0	13.1	17.9
M	1.85	4.05	6.7	9.3	12.65	16.0
N	1.7	3.8	6.4	9.0	12.9	18.2
O	1.85	4.0	6.5	8.75	11.2	17.0
P	1.8	3.85	6.2	8.05	10.0	13.6
Q	1.55	3.4	5.75	6.05	3.5	1.1
ΔP	5.45	12.1	18.2	25.25	35.2	-

TABLE 4-5
VELOCITY PRESSURES AFTER INSTALLATION OF COMB AT LEADING EDGE

Nom. Channel Velocity ft/sec	10	15	20	25	30	35
Total Loop Flow - GPM	180	270	360	450	540	630
Channel Letter	Velocity Pressure - inches Hg.					
A	1.0	2.3	4.05	6.3	11.4	12.9
B	.85	1.85	3.25	5.1	7.65	10.25
C	.8	2.05	3.7	5.7	8.95	12.0
D	1.1	2.35	4.5	7.3	11.5	15.9
E	1.05	2.3	4.2	6.8	10.25	13.9
F	1.1	2.35	4.0	6.45	10.0	13.7
G	.9	2.1	3.75	6.0	9.2	12.2
H	1.15	2.55	4.7	7.7	12.15	16.9
I	1.05	2.15	4.0	6.35	9.65	13.0
J	1.1	2.5	4.55	7.3	11.1	15.0
K	1.25	2.65	4.85	7.9	12.2	16.3
L	1.05	2.3	4.35	7.3	11.5	15.85
M	1.1	2.55	4.7	7.7	11.95	16.05
N	1.2	2.65	4.9	8.05	12.6	17.2
O	1.15	2.6	4.65	7.55	11.4	14.6
P	1.25	2.7	4.75	7.4	10.4	13.3
Q	.9	1.85	3.0	4.1	6.35	3.7
ΔP	6.7	13.7	22.4	32.35	-	-

TABLE 4-6
VELOCITY PRESSURES AFTER INSTALLATION OF COMB AT LEADING EDGE

Norm. Channel Velocity ft/sec	10	15	20	25	30	35
Total Loop Flow - GPM	180	270	360	450	540	630
Channel Letter	Velocity Pressure - inches Hg.					
A	1.0	2.35	4.35	6.75	12.1	14.4
B	.85	1.95	3.5	5.3	7.8	10.7
C	.85	2.1	3.90	6.05	9.15	12.5
D	1.15	2.6	4.75	7.7	11.6	16.25
E	1.05	2.45	4.45	7.1	10.4	14.3
F	1.0	2.25	4.2	6.95	10.2	14.2
G	.95	2.25	4.05	6.35	9.4	12.6
H	1.2	2.7	5.05	8.15	12.4	17.6
I	1.0	2.35	4.25	6.55	9.8	13.6
J	1.15	2.6	4.8	7.6	11.25	15.5
K	1.25	2.85	5.2	8.5	12.55	17.1
L	1.15	2.6	4.8	7.85	11.75	16.55
M	1.25	2.85	5.15	8.25	12.2	16.55
N	1.25	2.85	5.3	8.55	12.8	17.8
O	1.2	2.8	5.1	8.05	11.5	15.2
P	1.25	2.8	5.0	7.65	10.7	14.3
Q	.95	1.9	3.4	4.65	6.5	4.0
ΔP	6.0	12.25	20.7	30.85	-	-

4.3 CONCLUSIONS AND RECOMMENDATIONS

Results of the collapse tests verify that fuel elements containing welded plates have the stability to effectively oppose channel collapse when operating within design specifications. Test results further demonstrated that any tendency towards channel failure was not evident until the flow rate was increased to approximately 164% (540 to 630 gpm) of design (384 gpm). It was also shown that a welded fuel element equipped with combs at the leading (and trailing) edges provided additional insurance against channel collapse and plate defections, over the range of 0 to 630 gpm. Therefore, in accordance with these conclusions, appropriate recommendations have been made to reflect these improvements in the fuel element design.

FIG. 4-1
CHANNEL VELOCITY DISTRIBUTION PRIOR
TO CHANNEL COLLAPSE

CHANNEL IDENTIFICATION
NOMINAL ELEMENT FLOW: 540 g.p.m.
CHANNEL "F" COLLAPSED AT NEXT HIGHER FLOW RATE (630 g.p.m.)

FIG.4-2
PLOT OF CHANNEL VELOCITIES SHOWING
COLLAPSE OF CHANNEL F

Fig. 4-3 Comb Attachment for Fuel Element

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5.0 APPENDIX

5.0 APPENDIX

5.1 PRELIMINARY INSTRUMENTATION SET-UP PROCEDURE

The following items contain miscellaneous pertinent information relative to wiring, calibration, and installation of test instruments prior to making the vibration and collapse tests.

5.1.1 Vibration Pick-Up Transformer Installation and Wiring

Original plans recommended the installation of six linear variable differential transformer pick-ups for the vibration tests on both elements, but because of mounting difficulties, only four of the pick-ups were used in the testing of the second element (TIG welded). These were located as follows:

LVDT #2 - Plate # 13 - Upstream end.
LVDT #3 - Plate # 9 - Upstream end.
LVDT #4 - Plate # 6 - Downstream end.
LVDT #5 - Plate # 13 - Downstream end.

Appropriate shielding was applied to the primary and secondary leads to minimize coupling and feedback through the wiring and transformer windings. To prevent electrical leakage when submerged in the hydraulic loop, a potting material was applied at each transformer connection point and at all connectors.

5.1.2 Pick-Up Transformer Calibration

The transformers were first calibrated in air, with the element and transformers dry, but connected in a manner similar to a normal test set-up. The next calibration was taken with the transformers immersed in water.

Under these conditions, the secondary output voltages from three of the four transformers dropped about 75%. The element was then removed from the water loop and additional potting applied at all connections. When the element and transformers were again immersed in water the transformer output dropped by as much as 25%. Consequently, final calibrations were carried out while the transformers were submerged in water. A plot of the calibration curves is presented in Fig. 5-1 and 5-2.

5.1.3 Manometer Preparation

The velocity pressure measuring system finally evolved for the collapse tests was the result of considerable preliminary experimental work by the

Laboratory. This included design and fabrication of all the components, and the use of various fluids in the calibration of the manometers.

Early calibration attempts were conducted using chloroethylene (CCL_2), and tetrabromoethane (CHBr_2 CHBr_2), as manometer fluids. Due to velocity range limitations imposed by these light fluids, final manometer calibrations were made using mercury for the velocity pressure indicating medium.

Preparation of the hydraulic loop for the velocity measurements included the application of a sodium chromate water treatment process to remove any entrained crud in the flow loop.

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FIG. 5-2
TRANSFORMER CALIBRATION CURVES
2KC - 3VOLT PRIMARY

PRIMARY INPUT 2KC @ 3VOLTS

LVDT TRANSFORMER CALIBRATION

FIG. 5-3

PLATE DEFLECTION VS. SECONDARY VOLTAGE

VARIATION (ON MEMOSCOPE)

2KC-3VOLT PRIMARY

PRIMARY INPUT
2KC-3VOLTS

CALIBRATION FOR
MEMOSCOPE PHOTO'S