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OWENS-ILLINOIS LIQUID SOLAR COLLECTOR MATERIALS ASSESSMENT

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Prepared by the

National Aeronautics and Space Administration
George C. Marshall Space Flight Center, Alabama

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The Marshall Space Flight Center (MSFC) was requested by the Energy Research and Development Agency (ERDA) to assess the general suitability of the design and materials and to investigate certain failure modes of the Owens-Illinois (O-I) Sunpak solar energy collector system. The primary problem was the violent fracture of collector tubes, with attendant scattering of glass fragments, under boilout conditions.

This report presents the data and information generated during the materials analysis segment of this effort. These data were obtained during pressure testing of the individual tubes, performance testing of a complete array of tubes on the MSFC solar simulator apparatus, and in other investigations as noted. The information herein represents only the data directly associated with materials analysis and is not a comprehensive presentation of all the data compiled during the MSFC test program.

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TECHNICAL MEMORANDUM 78163

OWENS-ILLINOIS LIQUID SOLAR COLLECTOR MATERIALS ASSESSMENT

SUMMARY

From the beginning of this investigation it has been noted that the baseline drawings for the liquid solar collector exhibited a distinct weakness concerning materials specification where elastomers, plastics, and foam insulation materials are utilized. A relatively small effort by a competent design organization would alleviate this deficiency. Based on results obtained from boilout and stagnation tests on the solar simulator, it is concluded that proof testing of the collector tubes prior to use helps to predict their performance for limited service life. Fracture mechanics data are desirable for predicting extended service life and establishing a minimum proof pressure level requirement.

The temperature capability of this collector system has been increased as the design matured and the coating efficiency improved. This higher temperature demands the use of higher temperature materials at critical locations in the collector. The manifold nonmetallic materials (e.g., plastics, elastomers, and insulation) must be upgraded to provide capabilities consistent with those of the improved collector.

I. INTRODUCTION

The Marshall Space Flight Center (MSFC) was requested by the Energy Research and Development Agency (ERDA) to assess the general suitability of the design and materials and to investigate certain failure modes of the O-I Sunpak solar energy collector system. The primary problem was the violent fracture of collector tubes, with attendant scattering of glass fragments, under boilout conditions. Boilout occurs when the system is assembled, filled, and collecting solar energy but has no fluid flow through the system. Boilout of the trapped fluid (usually water) begins when steam is produced and the system pressure rises above that of the pressure relief valve (approximately 35 psig), venting steam and/or hot water with the gradual loss of the fluid charge in the system.

Boilout of the collector is no longer considered to be an acceptable mode of operation by O-I. They recommend that it should occur only during an operational failure of the system. Secondary problems were long-term materials degradation and loss of vacuum in the collector tubes. MSFC submitted a plan to ERDA which led to an analysis of these problems.

This report presents the data and information generated during the materials analysis segment of this effort. These data were obtained during pressure testing of the individual tubes, performance testing of a complete array of tubes on the MSFC solar simulator apparatus, and in other investigations as noted. The information herein represents only the data directly associated with materials analysis and is not a comprehensive presentation of all the data compiled during the MSFC test program.

II. O-I SUNPAK SYSTEM DESCRIPTION

A photograph of the assembled O-I system is shown in Figure 1. The 24 glass collector tubes are manifolded together so that the fluid flow is channelled sequentially through each individual tube. Figure 2 shows the configuration for a tube pair. It also shows the detail parts and components of the system. An individual collector tube (Fig. 3) consists of two concentric glass tubes, sealed together at one end, with a hard vacuum in the annular space between the tubes. A selective absorber coating, with high solar absorptivity and low emittance, is applied to the outer surface of the inner tube. The hard vacuum protects the vacuum-deposited metallic absorber coating from atmospheric degradation and suppresses gas conduction heat loss from the inner tube. The efficiency of this construction results in inner tube temperatures of approximately 650°F (340°C) when the tube is stagnated, i.e., exposed to full sunlight while filled only with air or steam, with no flow through the tube.

III. MATERIALS IDENTIFICATION

The initial step in the materials analysis was to identify each material called out in each component of the baselined design drawings. Additionally, an attempt was made to trace the materials in each component. Table 1 presents a listing of each component identified in the design drawings, the material from which the component is fabricated, and a note indicating whether or not adequate

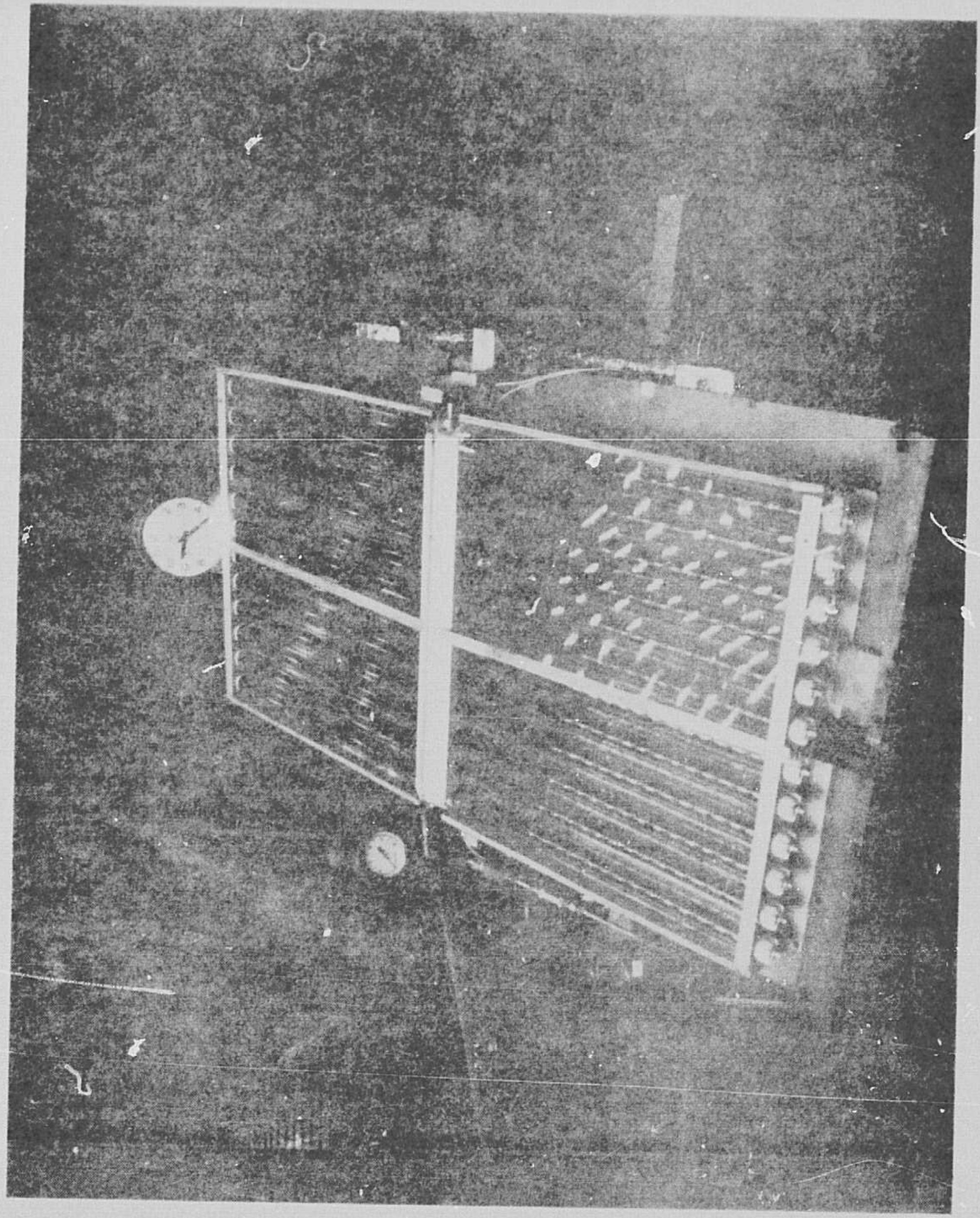

Figure 1. Assembled O-I Sunpak solar collector array.

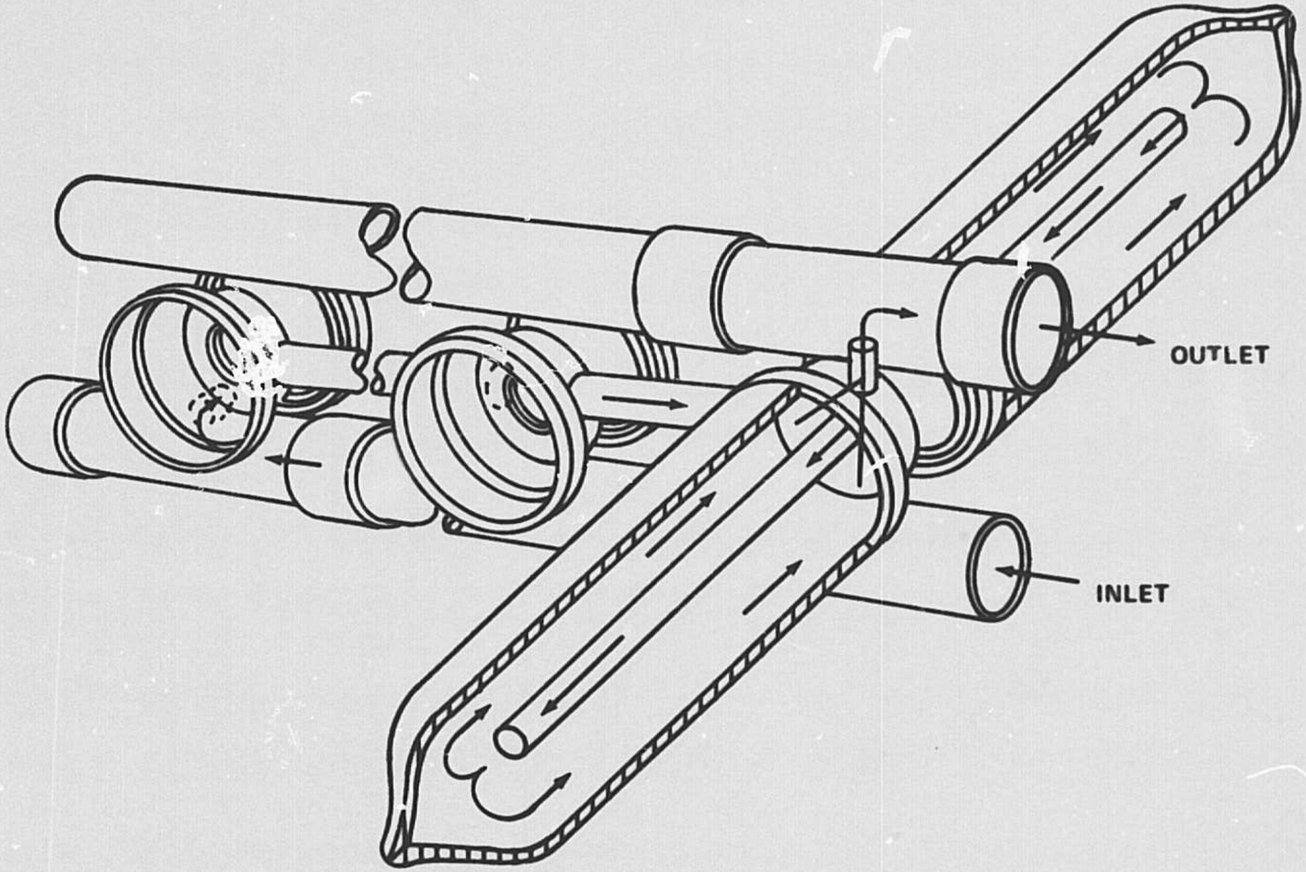

Figure 2. Fluid flow adjacent solar collector tubes.

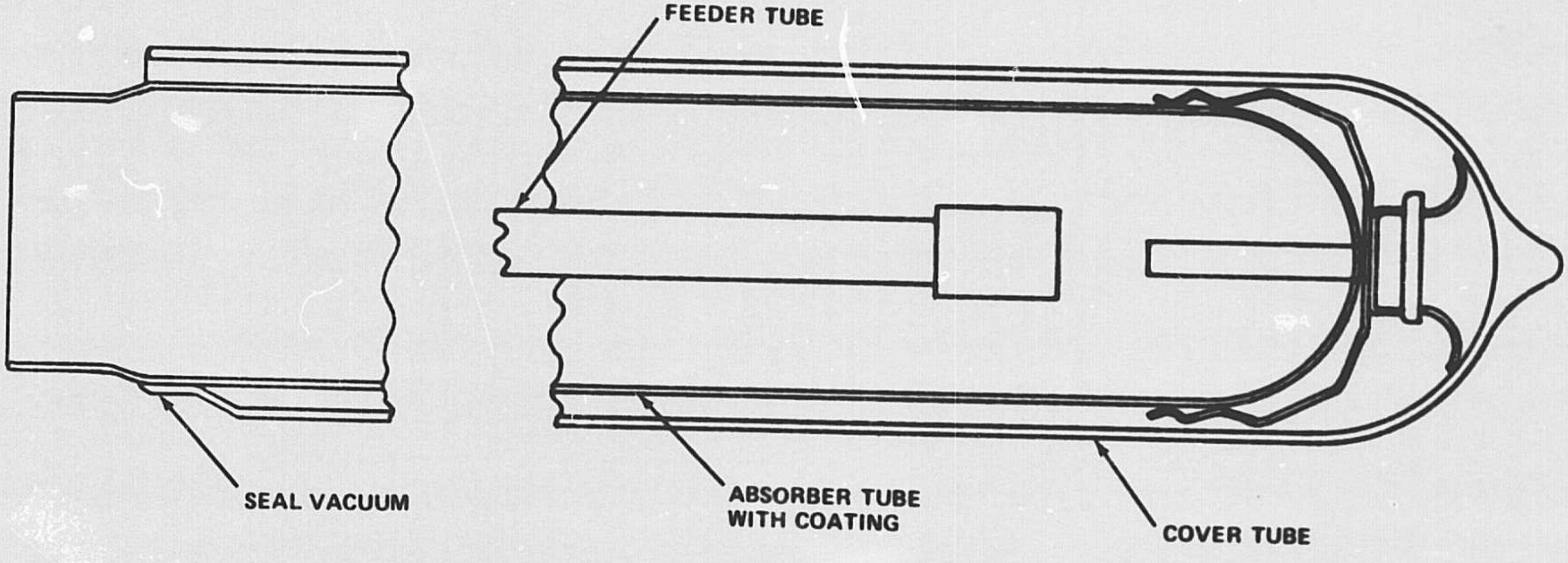

Figure 3. Collector tube.

TABLE 1. MATERIAL SPECIFICATIONS AND PROCESS RECORDS

Component Name	Component Material	Material Record
Collector Tube Assembly	KG33 Glass (Borosilicate)	Yes
Feeder Tube	KG33 Glass (Borosilicate)	Yes
Spring and Gettor Assembly	305SS/Barex No. 58	Yes
Foam Insulation	Isocynate Urethane (5T07 lb/ft^3)	Yes
Gelcoat Finish	Sanitary Ware Gelcoat (230000 Series)	Yes
Locator Bracket	16 ga. Steel	Yes
Solder	Welco No. 5 (96.5-Sn-3.5% Ag)	Yes
Flanged Cup	Soft Copper	Yes
Plain Cup	Soft Copper	Yes
Feed Tube and Extension	Hard Drawn Copper (Type M)	Yes
Tube Side Connector	Hard Drawn Copper (Type M)	Yes
O-Ring	Dow Corning Silicone (Diethyl)	Yes
Grommet	Silicone Rubber	No
Tube Coupler	305SS/Silicone Rubber	No
Shim Spacer	303-0 Aluminum	Yes
Tube Support Cup	Formula 103 Polycarbonate (Lexan)	Yes
Clip	3003-0 Aluminum	Yes
Tube Support	6061-T6 Aluminum	Yes
Reflector	5052 Aluminum/Glass Resin Finish	Yes
Manifold Support	Fiberglass/Resin	No
Tube Support Insert	Acrylo-Butadiene-Styrene	Yes
Feeder Tube Tip Protector	Silicone Rubber	No
Feeder Tube Connector	Silicone Rubber	No
Feeder Tube Coupler	Silicone Rubber	No
Tip-Off Protector	Vinyl	Yes
Channel "T" Nut	1010SS	Yes
Shim Spacer	3003-0 Aluminum	Yes
Seal Washer	Aluminum/Neoprene	Yes
Screw End Cap	2011-T3 Aluminum	Yes
Mounting Pad	Black Neoprene	Yes
Stop Screw	2011-T3/2017 T4 Aluminum	Yes
Center Bracket	303SS	Yes
Support Rod	303SS	Yes
End Seal	Silicone Rubber	No
End Cap Foamed	Cast Polyurethane Foam	Yes
Insulation Series Connector	Cast Polyurethane Foam	Yes
End Bracket	16 ga. Steel	Yes
Mounting Spacer	3003-0 Aluminum	Yes
Center Bracket	303SS	Yes
Tube Cup Connector	Hard Drawn Copper	Yes

materials records were available during the investigation. A negative indication in the "Material Record" column indicates that the available information is insufficient to corroborate that the proper material was used. **Improved control over the materials used in these items is obviously needed.**

IV. GLASS COMPONENT ANALYSIS

In addition to system reliability and economic problems, the major immediate problem with respect to the O-I system was the violent fracture of the glass collector tubes when boilout occurs. This failure had been observed only a few times, but the violence of the failure was sufficient to warrant concern about possible personal injury to anyone in the vicinity of the system. At the start of this investigation it was not clear whether these failures were due to poor quality collector tubes or to system requirements exceeding the capabilities of the collector tube regardless of its quality. For the system tests conducted on the MSFC solar simulator (an array of slide projector bulbs driven to simulate the total light energy of the Sun at the Earth's surface), the quality of the collector tubes was established prior to the test by dimensional inspection, visual inspection for cracks and flaws, and by proof pressure testing. The dimensional and visual inspection was conducted at Owens-Illinois, Toledo, Ohio and rejected tubes were deleted from consideration. Proof testing was conducted at O-I and at MSFC.

A. Proof Testing

The proof testing consisted of hydrostatically pressurizing the inner tube of the collector tube to 350 psig (2.4 MN/m^2). The proof pressure necessary to screen tubes on an absolute basis could not be determined from considerations of systems requirements and appropriate safety factors as these system requirements, in terms of pressure and temperature induced stresses, are not known. In addition, it is not known if the glass stresses resulting from proof pressure testing are in the proper location and direction to simulate the induced thermal stresses of operation in various modes, particularly the thermal stresses occurring during boilout. The 350 psi proof pressure was selected solely on the basis that it would stress the glass to a reasonably high level (4200 psi in the major portion of the tube based on nominal dimensions) without rejecting an unacceptable number of tubes and would provide a benchmark for possible future selection of a different proof pressure, depending upon the observed performance of tested tubes in simulator and demonstration arrays. It should be noted that this proof pressure is an order of magnitude greater than the system pressure under normal operating conditions, but that the glass is subject to other stresses (thermal, structural, vibrational, etc.), in addition to the pressure stress.

O-I proof tested 256 tubes to the selected 350 psi (2.4 MN/m^2) level with no dwell time at pressure, obtaining failure in 28 tubes (11 percent of those tested). Results of these tests are given in Table 2, where it may be noted that one tube failed at a pressure of only 155 psi and three tubes failed at 225 psi.

Seventy-seven of the tubes which survived the O-I proof test were delivered to MSFC to support this investigation. These tubes were given an additional proof test, again to 350 psi (2.4 MN/m^2), but with a 90 s hold at pressure. During this test, 24 of the 77 tubes failed, representing a 31 percent failure rate for these previously tested tubes. The data from this test are given in Table 3.

Data from an MSFC proof test of 44 previously untested production tubes are given in Table 4. The 350 psi (2.4 MN/m^2) pressure level was sustained for 90 s. Five tubes were broken during installation and seven tubes (18 percent of those tested) failed during test.

The results of these tests indicate that the requirement for a proof pressure test is well founded. An appreciable percentage of tubes receive relatively severe flaws in the production process, and they will fail under low glass stress, e.g. approximately 1880 psi in the case of the tube which failed at 155 psi pressure. It is also indicated that the 350 psi proof pressure in conjunction with the flaw size in a number of tubes produces stress intensity factors sufficiently high to produce substantial flaw propagation rates, as demonstrated by the increasing failure rate of tubes as the duration of exposure to pressure is increased. These results are not inconsistent with the expected quality of the tubes, considering the opportunities in the fabrication processes for the introduction of a flaw population of random severity.

A number of tests were run in which proof tested tubes, assembled in an array, were subjected to boilout and/or stagnation on the MSFC solar simulator. No failure was observed on tubes which had passed the 350 psi (2.4 MN/m^2) proof test. From these tests, it is concluded that 350 psi (2.4 MN/m^2) proof pressure test is adequate for short-term exposure to adverse operating modes.

The MSFC simulator was then operated using a set of tubes which had been proof tested and then intentionally scratched in the axial direction on the interior surface of the absorber tube. These tubes were exposed to boilout and

TABLE 2. PROOF TEST DATA

Tube No.	Batch No.	Pressure (psi)	Comments
222	A167	375	OK
208	A167	350	Tube failed at 350 psi
207	A167	350	OK
213	A167	350	OK
163	A167	350	OK
234	A168	350	OK
243	A168	350	Tube failed at 350 psi
238	A168	350	OK
235	A168	350	OK
233	A168	350	OK
239	A168	350	OK
242	A168	340	OK
214	A168	350	OK
244	A168	340	OK
215	A168	350	OK
202	A167	290	Tube failed at 290 psi
186	A167	350	OK
187	A167	350	OK
204	A167	350	OK
194	A167	350	OK
205	A167	350	OK
183	A167	350	OK
203	A167	350	OK
189	A167	350	OK
184	A167	350	Tube failed at 350 psi
181	A167	350	OK
201	A167	350	OK
182	A167	350	OK
177	A167	350	OK
221	A167	350	OK
169	A165	350	OK
173	A165	350	OK
175		315	Tube failed at 315 psi
161	A165	350	OK
168	A165	350	OK
167	A165	310	Tube failed at 310 psi
166	A165	350	OK
137	A165	350	OK
170	A165	350	OK
131	A165	350	OK
130	A165	305	Tube failed at 305 psi

TABLE 2. (Continued)

Tube No.	Batch No.	Pressure (psi)	Comments
160	A165	350	OK
164	A165	350	OK
165	A165	350	OK
156	A165	350	OK
132	A165	350	OK
169	A165	350	OK
158	A165	350	OK
159	A165	350	OK
162	A165	350	OK
140	A164	350	OK
152	A164	350	OK
151	A164	350	OK
154	A164	305	Tube failed at 305 psi
146	A164	350	OK
3	A164	350	OK
145	A164	350	OK
135	A164	325	Tube failed at 325 psi
155	A164	350	OK
148	A164	350	OK
149	A164	350	OK
136	A164	350	OK
139	A164	350	OK
133	A164	350	OK
143	A164	350	OK
147	A164	310	Tube failed at 310 psi
150	A164	225	Tube failed at 225 psi
141	A164	305	Tube failed at 305 psi
153	A164	280	Tube failed at 280 psi
53	A163	350	OK
72	A163	350	OK
107	A163	335	Tube failed at 335 psi
104	A163	350	OK
1	A163	350	OK
22	A163	350	OK
119	A163	305	Tube failed at 305 psi
58	A163	315	Tube failed at 315 psi
138	A163	350	OK
63	A163	350	OK
18	A163	350	OK
15	A163	350	OK
129	A163	350	OK

TABLE 2. (Continued)

Tube No.	Batch No.	Pressure (psi)	Comments
73	A163	350	OK
60	A163	350	OK
16	A163	350	OK
76	A163	350	OK
62	A163	350	OK
71	A163	350	OK
59	A163	350	OK
108	A162	350	OK
113	A162	325	Tube failed at 325 psi
144	A164	350	Broke tube after test
121	A162	350	OK
105	A162	350	OK
115	A162	350	OK
117	A162	350	OK
116	A162	350	OK
111	A162	350	OK
124	A162	350	OK
125	A162	300	Tube failed at 300 psi
112	A162	350	OK
114	A162	350	OK
128	A162	350	OK
120	A162	350	OK
122	A162	350	OK
123	A162	350	OK
77	A162	350	OK
79	A162	350	OK
78	A161	350	OK
98	A161	350	OK
94	A161	350	OK
100	A161	350	OK
103	A161	350	OK
102	A161	350	OK
90	A161	350	OK
86	A161	350	OK
84	A161	350	OK
80	A161	335	Tube failed at 335 psi
89	A161	350	OK
85	A161	350	OK
82	A161	225	Tube failed at 225 psi
83	A161	350	OK
92	A161	350	OK

TABLE 2. (Continued)

Tube No.	Batch No.	Pressure (psi)	Comments
95	A161	350	OK
93	A161	350	OK
99	A161	350	OK
97	A161	305	Tube failed at 305 psi
101	A161	350	OK
96	A161	350	OK
49	A160	350	OK, broke when taken out
48	A160	350	OK
47	A160	350	OK
35	A160	350	OK
32	A160	350	OK
31	A160	250	OK
28	A160	350	OK
29	A160	350	OK
24	A160	350	OK
27	A160	315	Tube failed at 315 psi
13	A160	350	OK
14	A160	350	OK
11	A160	350	OK
12	A160	350	OK
9	A160	350	OK
10	A160	350	OK
7	A160	350	Tube failed at 350 psi
8	A160	350	OK
4	A160	350	OK
5	A160	350	OK
371	A175	350	OK
411	A175	350	OK
191	A175	350	OK
33	A175	350	OK
134	A175	350	OK
30	A175	350	OK
355	A175	335	Tube failed at 335 psi
365	A175	350	OK
363	A175	350	OK
414	A175	350	OK
399	A175	350	OK
357	A175	350	OK
403	A175	350	OK
404	A175	350	OK

TABLE 2. (Continued)

Test No.	Batch No.	Pressure (psi)	Comments
398	A175	350	OK
378	A175	350	OK
402	A175	350	OK
226	A175	350	OK
407	A175	350	OK
323	A175	350	OK
387	A174	350	OK
374	A174	350	OK
401	A174	350	OK
373	A174	350	OK
389	A174	350	OK
376	A174	350	OK
375	A174	350	OK
377	A174	350	OK
372	A174	350	OK
396	A174	350	OK
370	A174	350	OK
400	A174	350	OK
379	A174	350	OK
406	A174	Not pressure tested, bad seal	
412	A174	350	OK
409	A174	350	OK
413	A174	350	OK
408	A174	350	OK
397	A174	350	OK
354	A173	350	OK
353	A173	350	OK
348	A173	350	OK
358	A173	155	Tube failed at 155 psi
345	A173	350	OK
352	A173	350	OK
359	A173	350	OK
360	A173	350	OK
344	A173	350	OK
350	A173	350	OK
349	A173	350	OK
362	A173	350	OK
364	A173	350	OK
342	A173	350	OK

TABLE 2. (Continued)

Tube No.	Batch No.	Pressure (psi)	Comments
369	A173	350	Hose ruptured after 350 psi, OK
347	A173	350	OK
366	A173	350	OK
367	A173	350	OK
361	A173	350	OK
332	A172	350	OK
335	A172	350	OK
340	A172	350	OK
336	A172	350	OK
293	A172	350	OK
321	A172	350	OK
333	A172	350	OK
334	A172	350	OK
252	A172	350	OK
315	A172	350	OK
341	A172	350	Tube failed at 350 psi
314	A172	350	OK
259	A172	350	OK
309	A172	350	OK
305	A172	350	OK
319	A172	350	OK
337	A172	350	OK
307	A172	350	OK
306	A172	350	OK
322	A171	350	OK
301	A171	350	OK
328	A171	350	OK
331	A171	350	OK
324	A171	350	OK
294	A171	350	OK
326	A171	350	OK
302	A171	350	OK
265	A171	350	OK
268	A171	350	OK
304	A171	350	OK
297	A171	350	OK
303	A171	350	OK
325	A171	350	OK

TABLE 2. (Concluded)

Tube No.	Batch No.	Pressure (psi)	Comments
270	A171	350	OK
267	A171	350	OK
291	A171	315	Tube failed at 315 psi
329	A171	350	OK
323	A171	225	Tube failed at 225 psi
260	A171	350	OK
216	A168	350	OK
230	A168	350	OK
231	A168	350	OK
224	A168	350	OK
248	A168	350	OK
245	A168	350	OK
246	A168	350	OK
251	A168	Pressure test not run, chipped absorber tube	

stagnation tests, and failures were observed. The surviving tubes were pressure tested to failure (Table 5). These tubes, with an average burst pressure of 266 psi, represent a slightly inferior group as compared to those breaking during proof pressure testing, but the observed failure of tubes from this set on the simulator test suggests that any substantial lowering of the proof test pressure might significantly increase the possibilities of failure in service.

To more accurately assess the absorber tube breaking stress, a series of absorber tubes without cover tubes were pressure tested to failure. The test calculations were based upon measured diameters and wall thickness. The wall thickness measurements were obtained by utilizing a Branson No. 101 digital caliper. This ultrasonic instrument permits thickness measurements without the use of a long thin probe inserted in the tube, which could scratch the glass surface. The diameter measurements were obtained from a mechanical vernier caliper. The tubes were wrapped with transparent tape after measurement to retain the glass fragments for fracture initiation studies.

The data obtained are given in Table 6. It may be observed that five of the nine tubes failed below 350 psi ($2.4\ MN/m^2$), a substantially higher fraction of failures at this level than was obtained in proof testing of complete tubes.

TABLE 3. MSFC PROOF OF TEST OF O-I SOLAR COLLECTOR TUBES

Tube No.	Burst Pressure (psig)	Failure Location (in. from open end)
A160-13	335	
9		Broke during installation
28	325	
24	Pass	
14	279	Close to seal
47	322	Close to seal
5	Pass	
4	319	Close to seal
29	Pass	
35	Pass	
8	349	
A161-85	348	12
83	Pass	
89	Pass	
90	341	15
84	Pass	
99	331	34
96	Pass	
101	Pass	
93	Pass	
92	Pass	
79	Pass	
121	Pass	
A162-108	Pass	
105	Pass	
115	318	
117	Pass	
A163-1	350	
15	350	22
16	Pass	
71	Pass	
76	Pass	
18	Pass	
104	Pass	
A163-138	350	Close to seal
A164-3	Pass	
155	349	Close to seal
145	Pass	

TABLE 3. (Concluded)

Tube No.	Burst Pressure (psig)	Failure Location (in. from open end)
146	350	Close to seal
152	Pass	
140	Pass	
149	Pass	
133	Pass	
143	Pass	
A165-169	Pass	
161	Pass	
168	350	
170	Pass	
160	350	Close to seal
157	Pass	
162	Pass	
159	Pass	
158	Pass	
164	Pass	
165	325	36
156	349	22
A167-163	Pass	
182	Pass	
A168-246	Pass	
244	Pass	
233	Pass	
234	Pass	
A171-297	350	12
270	326	
268	Pass	
302	Pass	
326	Pass	
331	Pass	
260	349	15
329	Pass	
A172-259	Pass	
305	Pass	
319	Pass	
A160-77	334	Close to seal
78	334	

TABLE 4. MSFC PROOF TEST OF O-I SOLAR COLLECTOR TUBES

Tube No.	Test Results
934-1	Broken during installation
934-2	Broken during installation
934-3	Pass
934-4	End too large for fixture
934-5	Pass
935-1	Pass
935-2	Broken during installation
935-3	Pass
935-4	Pass
935-5	Pass
935-6	Pass
935-7	Pass
936-1	Pass
936-2	Pass
936-3	Fail 340 psig
936-4	Pass
936-5	Fail 325 psig
936-6	Pass
936-7	Broken during installation
936-8	Pass
936-9	Pass
936-10	Fail 350 psig plus 30 s
936-11	Pass
937-1	Fail 345 psig
937-2	Pass
937-3	Pass
938-1	Fail 350 psig plus 30 s
938-2	Pass
938-3	Pass
938-4	Pass
938-5	Pass
938-6	Pass
938-7	Pass
938-8	Pass
938-9	Pass
938-10	Pass
938-11	Pass
938-12	Pass
938-13	Pass
938-14	Pass
939-1	Pass
939-2	Fail 341 psig
939-3	Pass
939-4	Fail 346 psig

TABLE 5. RESULTS OF PROOF TEST OF "USED TUBES" WHICH WERE DEFECTED

Tube No.	Burst Pressure (psi)
C-1	329
C-2	250
C-3	291
C-5	293
C-6	110
C-8	254
C-10	256
C-11	242
C-12	208
C-13	202
C-14	294
C-15	293
C-18	289
C-19	244
C-20	292
C-21	288
C-22	296
C-23	306
D-1	265
D-2	283
D-3	268
D-4	297
D-6	244
D-7	247
D-8	234
D-9	291
D-10	220
D-11	351
D-13	286
D-14	261
D-16	275
D-17	272
D-18	223
D-21	272
D-24	292

TABLE 6. PROOF TEST OF BARE ABSORBER TUBES

Tube No.	Wall Thickness (in.)				Outside Diameter (in.)				Burst Pressure (psig)	Failure Location (in. from opened end)	Calculated Stress At Failure (maximum to minimum, psi)
	1	2	3	4	1	2	3	4			
1	0.077	0.080	0.079	0.078	1.700	1.700	1.697	1.700	343	3	4334 to 4240
1	0.077	0.078	0.080	0.080	1.715	1.705	1.702	1.706			
1	0.076	0.077	0.079	0.080							
1	0.076	0.076	0.079	0.079							
2	0.078	0.079	0.078	0.080	1.753	1.766	1.725	1.715	339	1 1/16	4386 to 4212
2	0.079	0.083	0.079	0.079	1.756	1.768	1.730	1.724			
2	0.076	0.079	0.080	0.077							
2	0.077	0.078	0.081	0.073							
3	0.078	0.079	0.080	0.079	1.732	1.735	1.735	1.735	324	13/16	4088 to 4028
3	0.077	0.078	0.082	0.077	1.735	1.743	1.740	1.740			
3	0.077	0.076	0.079	0.080							
3	0.078	0.077	0.077	0.081							
4	0.076	0.078	0.075	0.076	1.700	1.700	1.703	1.700	381	42 3/4	4910 to 4591
4	0.076	0.076	0.075	0.075	1.717	1.703	1.709	1.703			
4	0.079	0.075	0.078	0.074							
4	0.081	0.080	0.077	0.079							
5	0.080	0.077	0.075	0.075	1.730	1.745	1.745	1.735	432	1 1/4	5246 to 5231
5	0.080	0.078	0.078	0.078	1.735	1.748	1.750	1.745			
5	0.080	0.079	0.079	0.079							
5	0.080	0.075	0.075	0.080							
6	0.081	0.075	0.074	0.074	1.700	1.700	1.700	1.695	339	2 1/8	4374 to 3984
6	0.077	0.079	0.077	0.078	1.705	1.708	1.715	1.700			
6	0.074	0.075	0.080	0.080							
6	0.076	0.074	0.075	0.078							
7	0.078	0.079	0.078	0.079	1.725	1.735	1.740	1.735	391	11/16	4856 to 4606
7	0.078	0.078	0.078	0.079	1.730	1.740	1.750	1.738			
7	0.079	0.079	0.078	0.077							
7	0.080	0.079	0.079	0.078							
8	0.082	0.079	0.077	0.077	1.728	1.733	1.725	1.718	365	1 7/8	4486 to 4307
8	0.080	0.081	0.078	0.076	1.734	1.738	1.735	1.728			
8	0.079	0.079	0.081	0.076							
8	0.079	0.080	0.078	0.080							
9	0.081	0.081	0.081	0.082	1.720	1.720	1.720	1.715	300	1	3981 to 3567
9	0.077	0.076	0.073	0.078	1.730	1.734	1.728	1.720			
9	0.076	0.074	0.077	0.074							
9	0.073	0.078	0.080	0.077							

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A probable cause of this occurrence is discussed in Paragraph IV.B. The breaking stress was calculated from the vector sum of the hoop and axial stresses, i.e.,

$$\sigma = \frac{pr}{t} + \frac{pr}{2t} = \frac{1.12\ pr}{t}$$

where

σ = stress at failure

p = pressure at failure

r = tube radius

t = wall thickness .

For each tube, dimensions reflecting the minimum thickness/maximum diameter and the maximum thickness/minimum diameter for the measurement set nearest the break were used to calculate the breaking stress, yielding two values of stress which would be expected to bracket the true stress at the exact failure location. These calculated stresses range from 3600 to 5200 psi (25 to 36 MN/m^2).

B. Fracture Initiation Studies

The fracture initiation site on any fractured glass appears as a straight, mirror surface surrounded by a distinct, gray-colored area, termed the stippled area. The fracture will then branch and propagate in both axial directions, creating long spiraling slivers of glass. These slivers typically point to the initiation surface. Figure 4 shows a typical fracture pattern created by pressurization of a tube.

Fracture studies of the complete collector tubes which broke during proof testing consistently indicated that the fracture initiated at a defect or scratch on the internal surface of the absorber tube. These defects are attributed to scratches and checks generated during manufacturing and inspection processes. Similar studies on the bare absorber tubes, which were pressure tested to failure, show that the fracture initiation site was consistently on the outside surface of the tube and that, again, an observable defect such as a scratch or check was present at the initiation site.

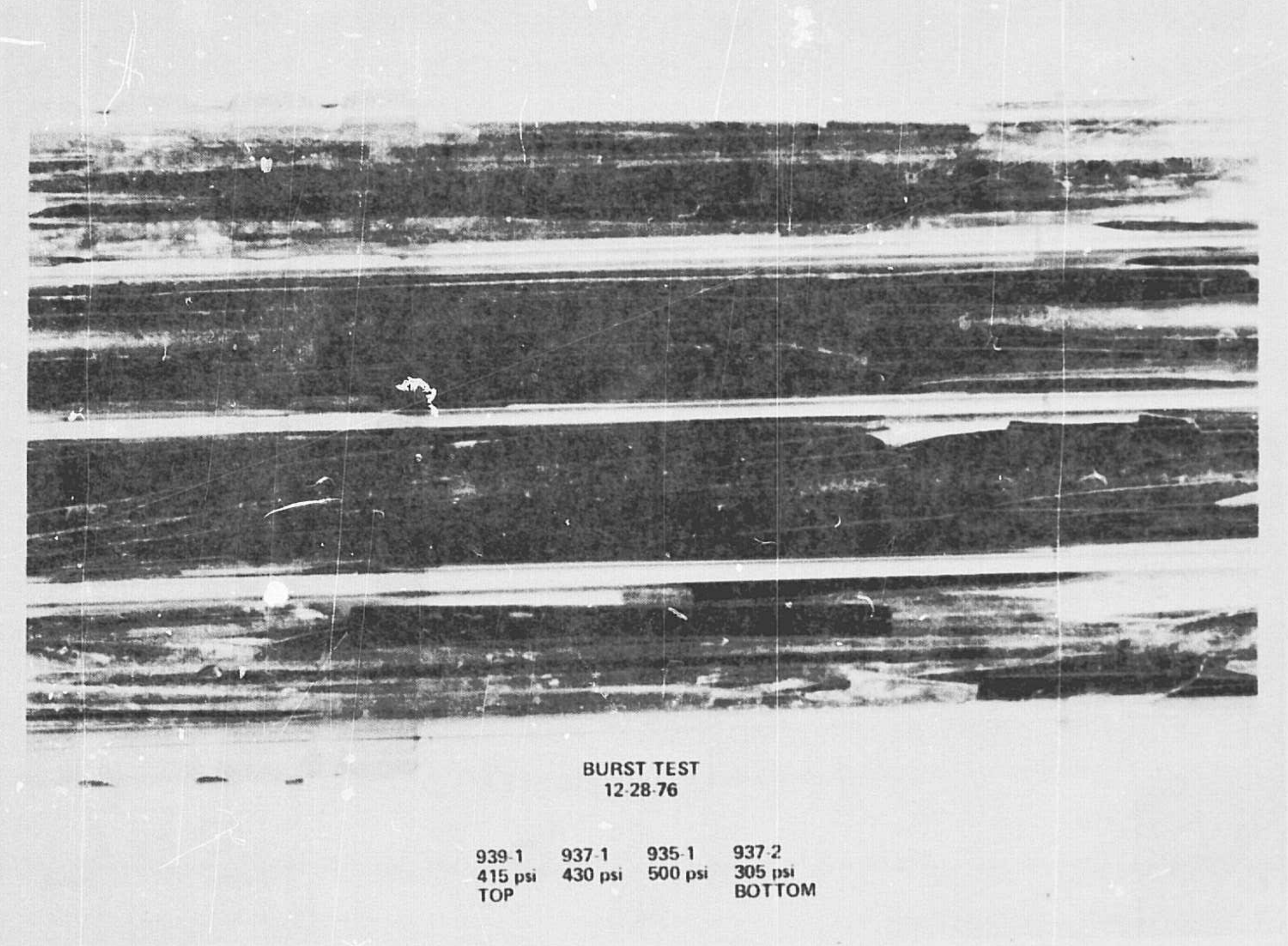

Figure 4. Typical fracture pattern.

In the case of the bare absorber tubes tested to failure, the fact that these tubes were not subjected to the normal measuring, inspection, and fabrication processes of collector tube manufacture undoubtedly accounts for all initiation sites appearing on the external surface (i.e., the internal surface has not been rubbed or scratched by any jigs or fixtures while the external surface has been subjected to some abuse, producing the scratches, checks, or rubs that are failure initiation sites). In testing complete collector tubes to failure, potential initiation sites on the exterior surface of the absorber tube are inhibited from slow flaw growth to failure by the vacuum in the annular gap between tubes. This moves the initiation site to the interior surface of the absorber tube because the water hydrotest fluid causes the stress corrosion induced slow flaw growth, entirely consistent with the experimental results of flaw growth studies.[1] It is also indicated that the magnitude of the flaws produced on the interior surface of the absorber tube during collector tube manufacture is similar to those on the exterior of the tube. Thus, minimizing the production of these defects on the internal surface would reduce the losses during proof pressure testing.

Fracture initiation surfaces could not be identified when failure occurred during boilout and stagnation tests on the MSFC solar simulator (using intentionally defected tubes as described previously) because the violent failures scattered glass over the array and floor.

C. Thermal Shock/Thermal Stress

At the onset of this investigation, it was postulated that tube breakage was occurring as a result of percolation of water in the feeder tubes during boilout. Percolation was not observed during the boilout test conducted on the MSFC solar simulator. One incident in which the feeder tube of a lower tube became uncoupled was observed. This observation was made after the collector tube had fractured violently and may have occurred during the failure. This tube had been intentionally defected with axial scratches. The failure of tubes in the absence of observed percolation demonstrates that percolation is not necessary to produce failures in tubes containing serious flaws, whether the flaws are intentional or the result of manufacturing operations.

Tube failure on the simulator was observed only with defective tubes during the second day of boilout, consistent with the performance of O-I collectors at several demonstration sites. One "good" tube ruptured violently

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[1] Weiderhorm, S. M., "Subcritical Crack Growth in Ceramics," Fracture Mechanics of Ceramics, vol. 2, Bradt, Hasselman, and Lange (Editors). Plenum Press, New York, N. Y., 1974, pp. 613-646.

during a hot-fill operation. No measurable system pressure was observed at the time of this failure. Hot-fill is presently an unacceptable mode of operation, according to O-I.

From the results of these tests, it appears that tube failure may occur due to stresses induced in the glass of a tube which contains a water level surface. This stress is caused by the temperature gradient in the tube, as the temperature of the glass increases with axial distance from the water level, from 240°F (115°C) to the stagnation temperature, 675°F (357°C). Moving water levels caused by boiling and pressure buildup also contribute to these stress gradients. It is believed that the expansion in the axial and circumferential directions is more critical than that across the wall thickness, since the glass tube thickness is relatively small.

D. Residual Stresses

Residual stresses were observed in the collector tubes in the area of the O-ring seal surface and vacuum tip-off area. These stresses were estimated to be of low level (a few hundred psi), using a polarimeter. No failure initiation points were observed in the seal or tip-off area. Some were observed close to the seal; however, they were attributed to scratches or checks in the glass surface. At this time, it is not believed that these residual stresses contribute significantly to the glass failures.

E. Fracture Mechanics

Fracture mechanics data are not available for the KG-33 borosilicate glass at the temperatures to which the glass is exposed in normal operation or the more severe boilout and stagnation operational modes. These data would be highly desirable and would provide a rationale for establishing the proof pressure test level in terms of the required service life and the stress levels and durations to which the glass is exposed in service. In conjunction with thermal and stress analyses, these data would establish the tube requirements for boilout, stagnation, and/or hot-fill operations. The alternative is to acquire service life data over a period of years to obtain insight into flaw propagation and failure rates as a function of operational conditions.

F. Glass Components Summary

Based on the results obtained from simulator testing, proof tested tubes appear acceptable for operation, including stagnation and boilout modes. These tests were conducted for short periods of time; therefore, long-term service life or service performance with continued stagnation/boilout cannot be predicted. This can be established only by testing and/or fracture mechanics studies. As with any glass manufacturing, the processes utilized should minimize the damage to the absorber tube. Additionally, it is desirable to redesign the cover tube dome end to a conical shape for better glass distribution and improved mating with the tube support cup insert.

V. COLLECTOR TUBE SELECTIVE COATING AND PRESSURE

The element which results in heat absorption is a two layer selective coating. The outer layer acts as an absorber of solar energy while the inner layer serves as a reflective baffle to radiation which would otherwise be transmitted through the vacuum between the absorber and cover tubes. The maximum temperature observed during testing in the solar simulator was 675°F (357°C) on the absorber tube. The coating is relatively stable and is protected by the vacuum; however, the coating degrades under certain conditions. The coefficients of thermal expansion of the coating and substrate glass are significantly different and peel-off can occur with repeated thermal cycling. Additionally, according to tests run by O-I, the absorption efficiency is found to decrease rapidly when the coating is subjected to temperatures above 700°F (371°C). In these tests, collector tubes were held at elevated temperature for an extended period of time, then allowed to heat in the Sun to its stagnation temperature. The temperature achieved during stagnation is a measure of the coatings absorption efficiency.

The O-I collector is designed and fabricated with a pressure of less than 10^{-4} torr between the absorber and cover tubes to minimize the loss of heat due to gas conduction. Tests run by O-I detected outgassing species which include water vapor, H_2, CO, CO_2, and CH_4. Each of these species is absorbed by a barium getter located in the evacuated cavity. It is believed that the bake-out procedure which is used to clean the components prior to their being sealed together is critical in assuring that quantities of outgassing do not occur which will result in a significant rise in pressure of a finished tube. Good quality control should be sufficient to suppress this potential problem area.

Helium diffusion from the atmosphere into the evacuated cavity could result in an increased pressure over a long period of time. This diffusion is dependent on temperature. According to calculations from data supplied by O-I, the pressure inside the evacuated cavity should be 3.5×10^{-3} mm after a 7.4 year exposure of the cover tube at 77°F (25°C) in an atmosphere with a helium partial pressure of 4×10^{-3} mm. At this time, helium diffusion does not appear to be a critical problem.

VI. MANIFOLD COMPONENTS

A. Soldered Copper Cups, Tubes, and Fittings

The liquid flow in the collector is channeled from one tube pair to the next by copper tubing and cups shown in Figure 5. These individual components are soldered together with Welco No. 5 solder (95 percent tin, 5 percent silver) which melts at approximately 435°F (224°C). The maximum temperature observed near a soldered component during boilout and stagnation on the solar simulator was 495°F (257°C) at the cups.

Soldering does not appear to be an adequate process for fabricating the cup assemblies. The flow of the solder, due to gravitational force, does not fill the joint as desired; the surface area in the joint is relatively small for a soldered assembly carrying loads; and the melting point of the solder is too low for the temperatures observed in stagnation/boilout.

Two alternatives are potential solutions to these problems. O-I could utilize a fully cast precision manifold where no soldered joints are necessary, or they could redesign the manifold and braze the components together. The present design does not lend itself to brazing because of the high probability of distortion due to creep and thermal expansion differences in the cups and tubing.

B. Foam Insulation Materials

The maximum temperature observed by a thermocouple submerged in the foam insulation surrounding the manifold was 220°F (104°C), except at the copper cups which was 495°F (257°C). At the cups, the insulation appears to degrade for a short distance until the temperature drops to a point where it does not damage the foam. No significant degradation of the foam was observed during testing on the solar simulator.

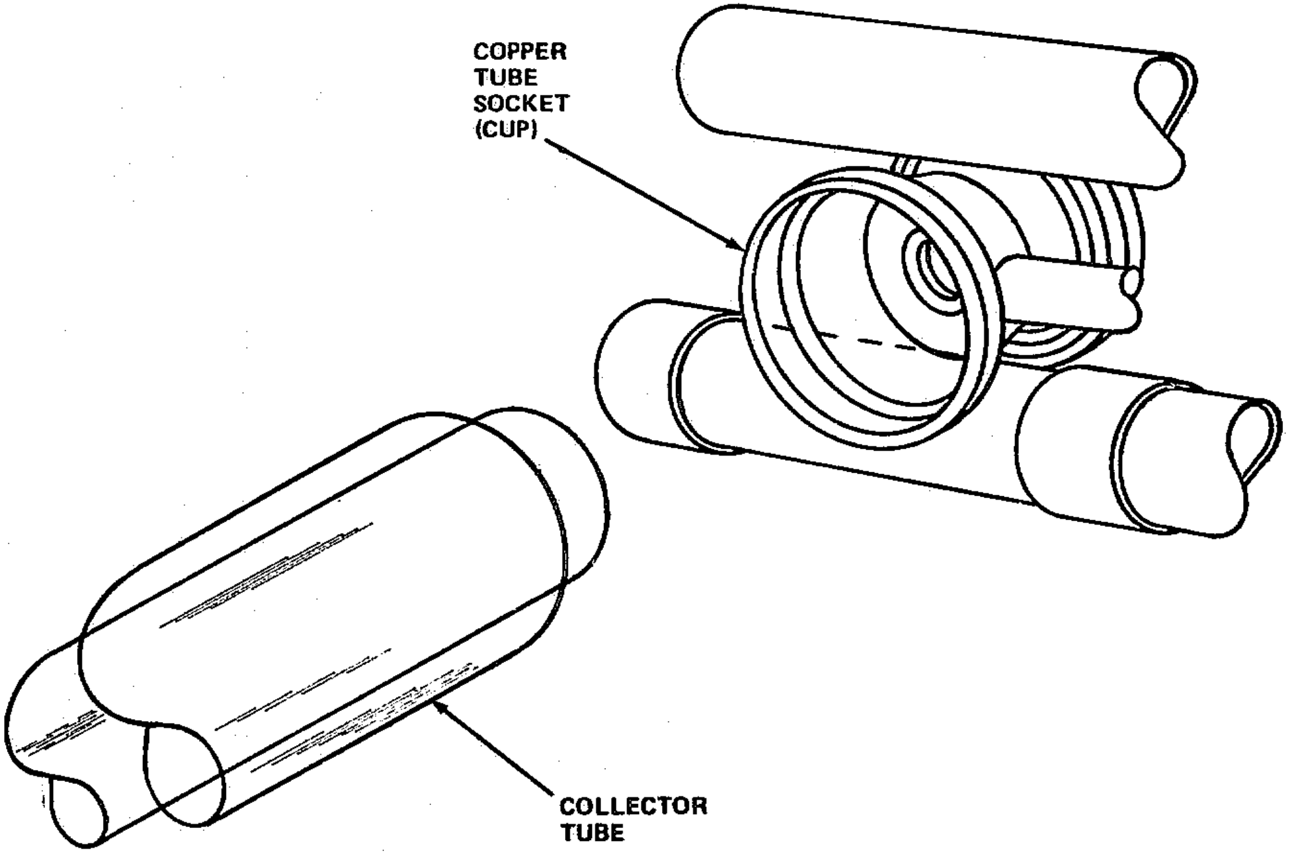

Figure 5. Copper tube socket.

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Formulation and proper mixing of the foam components are considered to be a critical step in assuring that the foam material does not degrade. If the foam insulation proves to be a problem area, higher temperature foams are available. Two of these are a high temperature polyurethane (300°F, 149°C) produced by Polymer Development Laboratory, Santa Ana, California and isocyanurate foams (350°F, 177°C) produced by Foam System Corp., Riverside, California.

C. Insulation Cover

The baseline design identified the insulation cover material as a sanitary gelcoat. The maximum temperature observed at this item was 205°F (96°C). The problem with this material is that it tends to deform with heat. An alternative to the gelcoat is a fiberglass reinforced polyester composite material for this component.

VII. PLASTIC COMPONENTS

The tube support cup insert (Fig. 6) is the only plastic component identified as a potential problem area. A maximum temperature of 205°F (96°C) was observed at the position of this part. The problem encountered is deformation of the cup insert due to thermal softening during the boilout mode of collector operation. This component could be redesigned to a conical shape to improve distribution of the load transferred to it from the collector tube's closed end. Fabricating this part from a higher temperature material than acrylic-butadiene-styrene (such as polycarbonate or polysulfone) should alleviate this problem.

VIII. RUBBER COMPONENTS

The O-ring and end bumper seals appeared to retain their resilience after exposure to a maximum temperature of 495°F (257°C) during boilout on the solar simulator. These parts are presently made from dimethyl silicone. Should they prove to be a problem in the future, one could increase their temperature capability by fabricating them from a methyl phenyl silicone.

The tip protectors used to prevent the feeder tubes from abrading the internal surface of the absorber tube are a problem area. These parts became

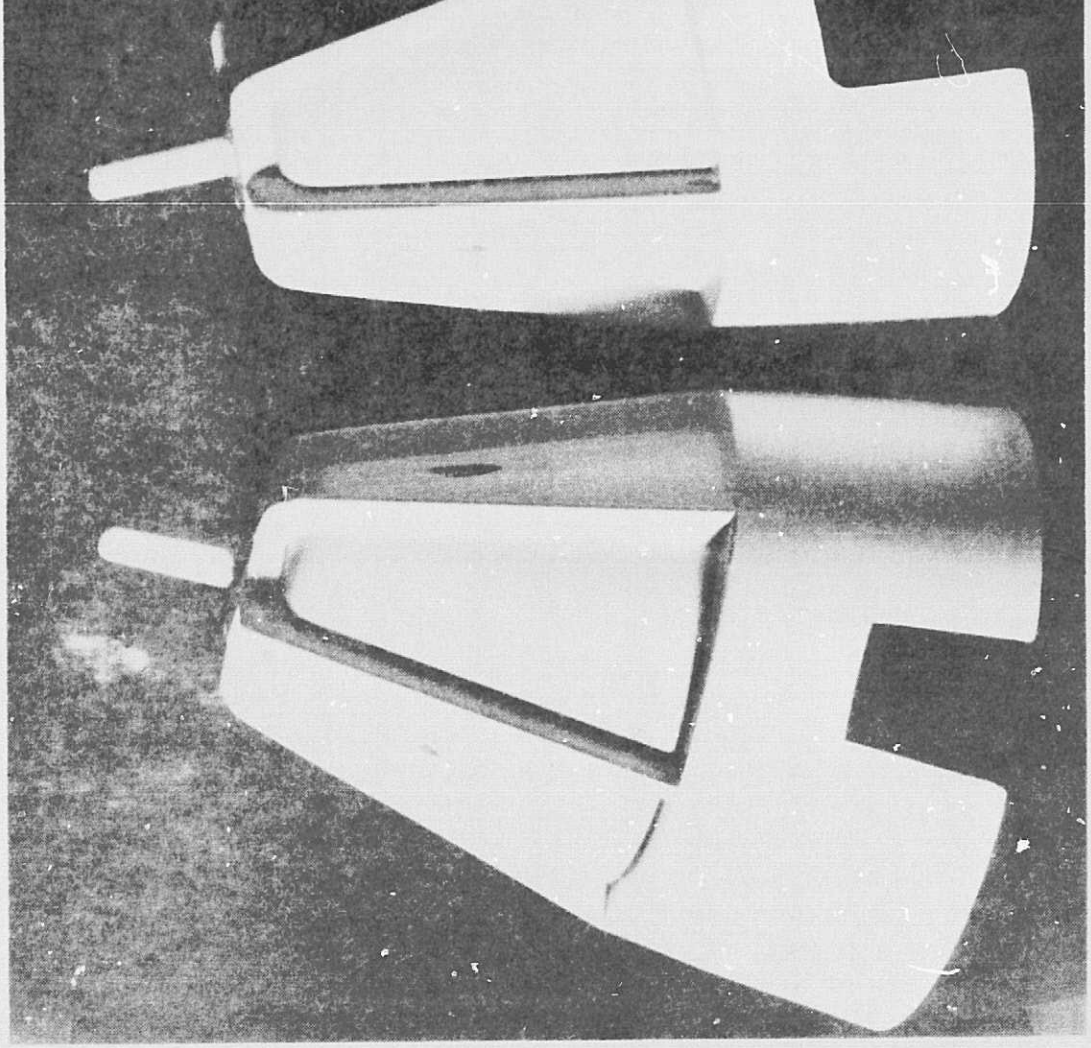

Figure 6. Tube support cup insert.

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"putty-like" after operation of the collector where they were exposed to 675°F (357°C). The life of this component should be prolonged significantly by utilizing a methyl phenyl silicone or possibly a carbon material for this component.

The feeder tube connector was not observed to degrade during testing; however, one tube exhibited a disconnected feeder tube after failure. It is not known if this occurred prior to or during tube failure. If the feeder tube disconnected and dropped to the bottom of the absorber tube prior to failure, it could have contributed to failure by permitting percolation of the residual liquid in its tube. This potential problem can be alleviated by redesigning the grommet to extend outward a distance adequate to allow the feeder tubes to be inserted in each end of the grommet. Since the grommet was observed to be subjected to 495°F (257°C), it also should be made of methyl phenyl silicone.

IX. CONCLUSIONS

The conclusions presented are based on tests conducted utilizing the baseline O-I solar collector in boilout conditions. The boilout mode is considered to be the most demanding environment that the collector might encounter.

It is necessary to proof pressure test glass tubes after their completion and prior to installation in a collector. The optimum proof pressure has not been established; however, it is believed that 350 psi (2.4 MN/m^2) for a very short duration should be adequate. Analysis of the fracture mechanism of glass subsequent to the proof pressure testing described in this report indicates that a sustain at 350 psi (2.4 MN/m^2) is not advantageous.

The feeder tube tip protector is considered to be inadequate since it degrades and loses its resiliency at the high temperatures of stagnation. A higher temperature material must be considered for this component.

Although specific failures were not identified in this area, it is believed the system would be improved by redesigning the connection between the two feeder tubes. The grommet which protects the feeder tube from the manifold could also serve to connect the two halves of the feeder tube together. This would move the feeder tube connector into a lower temperature environment.

The solder used to assemble the manifold softens at a temperature very close to those observed during boilout conditions. The components should be brazed together provided the copper is not fully annealed during the process. The optimum manifold system would be one which is a monolithic casting. This would eliminate seal leakage and improve the tolerance achievable on the manifold.

These recommendations should improve the integrity of the collector from a materials standpoint. An assessment of the impact of implementing these recommendations on the cost of the collector must be made and the confidence level established for the system.

APPROVAL

OWENS-ILLINOIS LIQUID SOLAR COLLECTOR MATERIALS ASSESSMENT

By R. L. Nichols

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

R. J. Schwinghamer

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