DOE/NASA TECHNICAL MEMORANDUM

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FINAL REPORT ON MSFC ASSESSMENT OF OWENS-ILLINOIS SUNPACK™ COLLECTOR PROBLEMS

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SUMMARY

From the beginning of this assessment of problems experienced in the application of the Owens-Illinois SUNPAK^{TM} liquid evacuated tube solar collector, three basic weaknesses were noted: lack of configuration control to establish a standard baseline design, lack of control on production processes as well as suitable acceptance tests for delivered hardware, and a lack of "applications" engineering to aid proper system design and installation of the collector by users. A MSFC plan [1] for analysis and test was implemented. This activity demonstrated the integrity of the baseline collector and produced recommendations to minimize problems in future system applications. Key recommendations include proof testing collector tubes prior to use, improved materials for manifold, plastic and rubber components used in the collector assembly, and interface constraints that must be considered in solar system designs using this collector. Also, Owens-Illinois has supported retrofit of collectors in earlier applications to successfully preclude recurrence of the problems.

I. INTRODUCTION

The Energy Research and Development Agency (ERDA) requested the Marshall Space Flight Center (MSFC) to participate in a detailed assessment, including independent tests, to help solve problems encountered with the Owens-Illinois SUNPAK^{TM} solar collector installed in several ERDA solar system demonstration sites. An immediate objective was to determine the risk to proceed with installation of these collectors on the General Services Agency building in Saginaw, Michigan. Problems related to loss of vacuum and/or violent fracture of the evacuated glass collector tubes, fluid leakage, freezing, flow anomalies in collector loops, manifold damage, and other system component failures.

On December 16 and 17, 1976, Owens-Illinois briefed MSFC and ERDA representatives on the problem history and prior steps taken to alleviate the problems. These discussions showed three basic weaknesses in the Owens-Illinois (O-I) activities:

a) Lack of rigorous configuration control to assure a baseline design definition and test and/or analytical validation of the design and design changes prior to production

b) Lack of rigorous control on production processes and suitable acceptance tests to validate that production quality assures design integrity in delivered hardware

c) Lack of "applications" engineering to preclude faulty system design and installation of the collector by a user.

A MSFC plan [1] was structured to work with O-I personnel to accomplish the following specific objectives:

a) Establish the baseline design, production processes, and quality assurance at this time

b) Factory tests to validate the baseline hardware to be used for testing

c) Site inspection and tests of hardware to validate hardware integrity after shipping

d) Assemble hardware in accordance with baseline instructions

e) Conduct selected tests to subject baseline collector(s) to field conditions

f) Assess risk factors associated with each anomaly noted during tests

g) Recommend product improvement options if risk assessment shows it is not desirable to continue use of the collector in its current baseline design.

The planned schedule extracted from Reference 1 is shown in Figure 1. ERDA decided that O-I would conduct tests in Andover, Massachusetts, on an array containing more than one collector in parallel with solar simulator

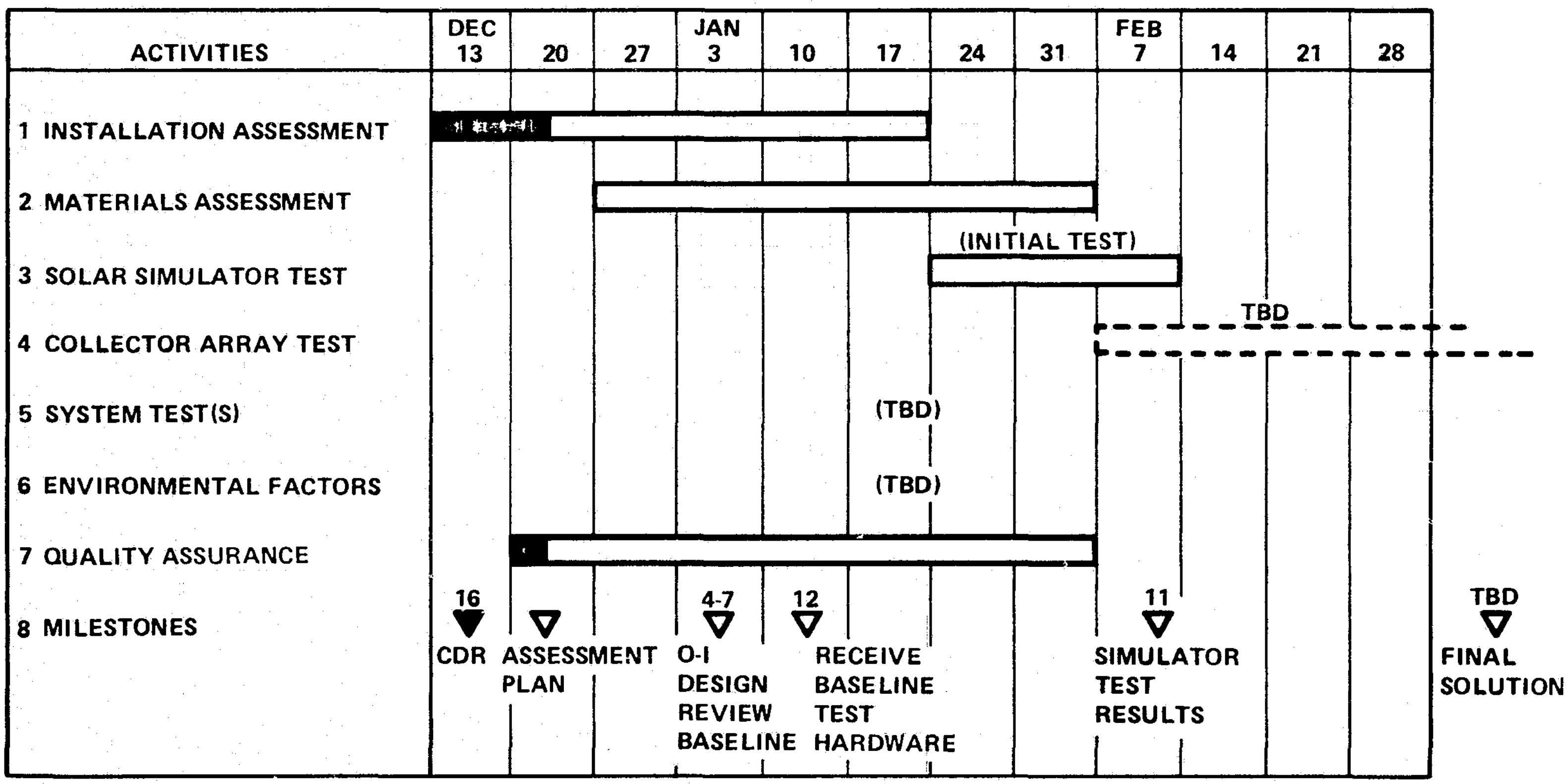

Figure 1. SUNPAK^{TM} assessment plan – preliminary schedule and milestones.

testing at MSFC on a single collector. That activity will be reported separately by O-I documentation. Likewise results from system test(s) and environmental factors evaluations would be documented by O-I as more field experience was gained from users of this collector.

II. BASELINE DESIGN DEFINITION

Because most planned applications for the O-I SUNPAK^{TM} collector would use the shaped reflector, this configuration was established for the hardware to be used in the MSFC assessment. Also, the reflectors allowed higher collector temperatures and provided worse case conditions relative to the spectrum of problems being investigated. Figure 2 shows the baseline collector as it was assembled for solar simulator tests. Figure 3 is a cross section view identifying the internal feeder tube and manifold passages that circulate fluid in the collector.

The following redlined assembly drawings defined the test hardware in February 1977:

SK-2064	Outboard Assembly (2 sheets)
SK-2060	Collector Tube Assembly
SK-3042	Manifold Assembly
SK-2988	Reflector
SK-3047	Tube Coupler
SK-2324	Manifold Innerconnections Solar Energy
SK-2049-1	Feeder Tube
SK-3041	Manifold Brazing Assembly.

These drawings, as well as lower level detail drawings, were studied to establish design sufficiency and materials compatibility. Section V discusses design aspects and Section VI addresses the materials deficiencies uncovered. Table 1 lists all the materials used in the SUNPAK^{TM} collector [2]. It is noteworthy that materials problems were found to be related to those items where process records for the baseline hardware were not available or insufficient to corroborate that the proper material was being used.

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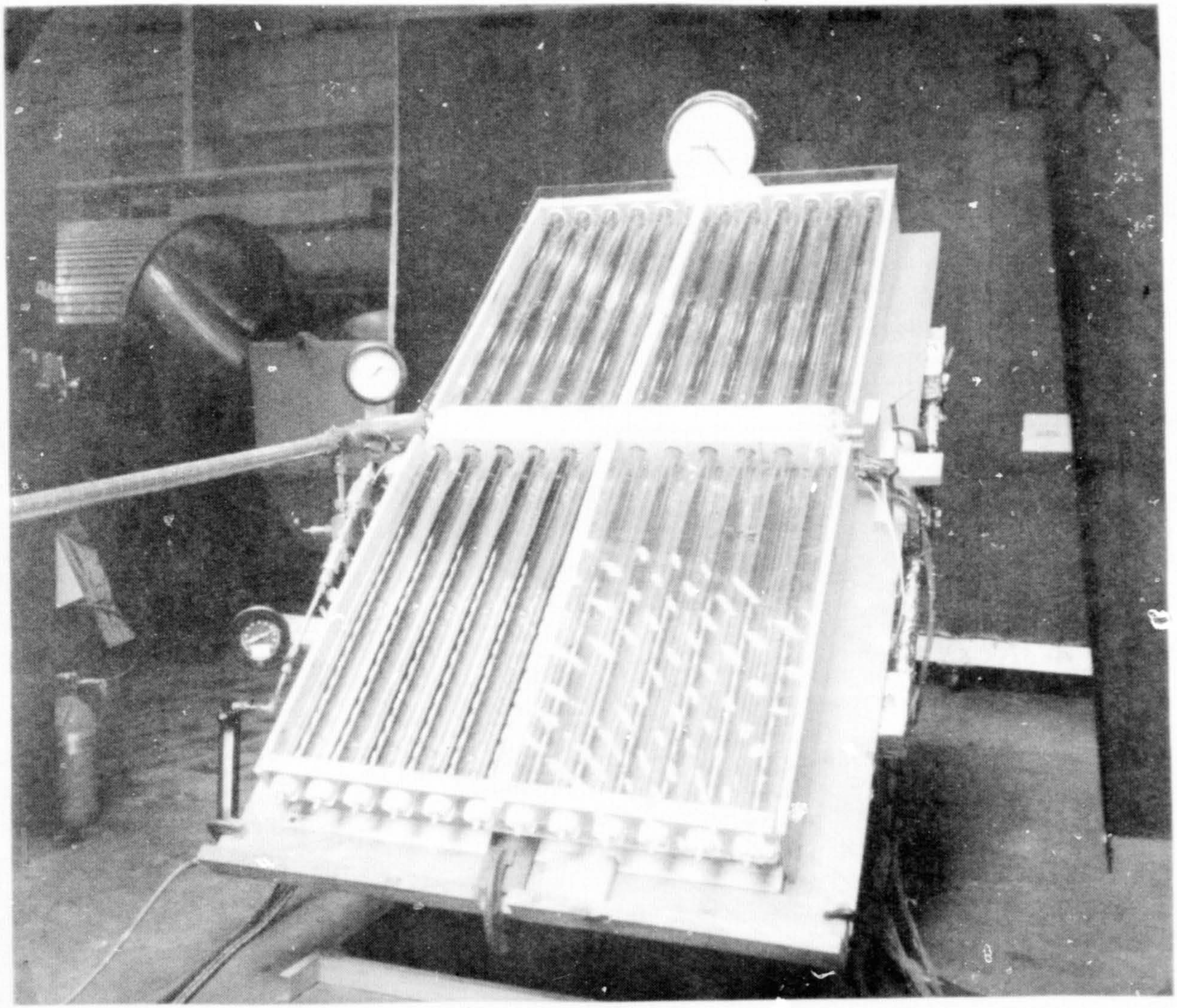

Figure 2. Baseline SUNPAK^{TM} collector assembled for test.

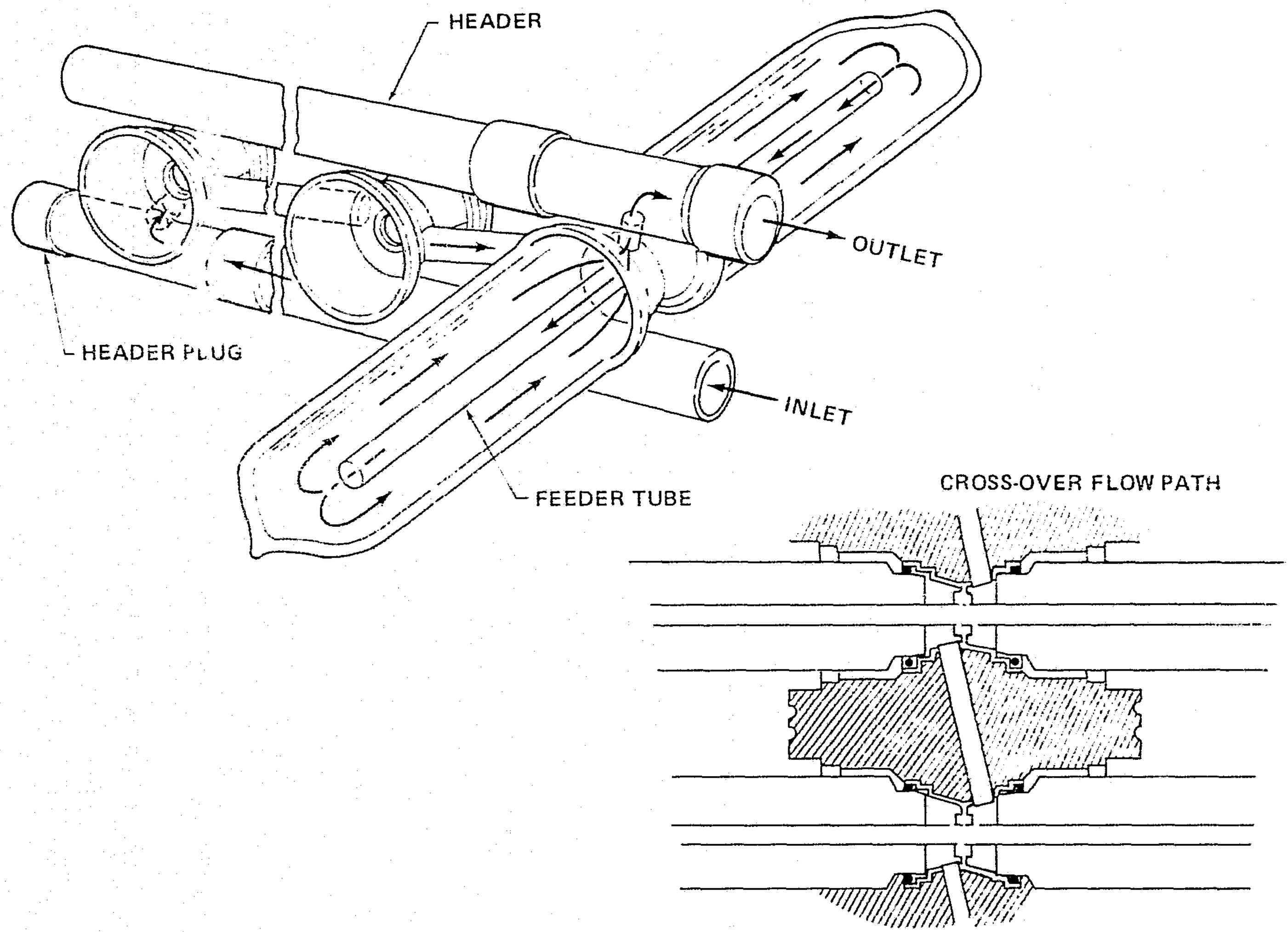

Figure 3. Internal view of SUNPAK^{TM} collector.

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

III. SYSTEMS SURVEY [3, 4]

Some system characteristics and site experiences were evaluated to determine if tube fractures, or other problems, could be correlated with system characteristics or design. Table 2 identifies the systems and site locations considered in this assessment. Data were gathered by site visits, telephone conferences with system designers and site engineers, and conferences with representatives of O-I. Assessment of system design characteristics, summarized in Table 3, is more qualitative than quantitative due to the low number of operational systems and their varying operating hours. Baseline data from comparable systems were not available, therefore, no reference existed. It is important to note that all systems were in fact experimental in that components and system configurations have been changed as experience was gained.

Only systems 3 and 6 were originally designed to utilize boilout and collector stagnation as system operational modes for collector drainage and rejection of excess energy. Other systems attempted to drain collectors by using drain valves on collector inlets/outlets and depending on gravity flow of collector fluid. The collector design precludes complete drain in this mode. Except for two systems, most others used multimode operation or other techniques to manage excess energy as shown in the table. To avoid unwanted boilout and collector stagnation during no-flow conditions caused by power failure or system malfunction, all system designs used a city water top-off scheme to limit collector fluid temperatures by continuous water flow.

Overpressure protection for most systems is provided by relief valves set at 25 to 30 psi. These valves are typically located near the collectors and are made redundant. The variation in numbers and locations for relief valves indicates that system designers differed on the best approach for overpressure protection. Systems 3 and 8 have no relief valves and are vented to atmosphere at all times.

Freeze protection for the systems studied varied between none, simple piping insulation and/or antifreeze solutions, and active warm water purge approaches. The freeze protection approach at site 9 is not known. Generally the approach is dictated by the low temperature extremes at the site locations and the cost and complexity desired for the system design.

TABLE 2. SYSTEM IDENTIFICATION

User	Area	Applications	System Sketches	Storage Tank Open/ Closed	City Water Top-Off
1. IGT/ L. A.	500	Test	Yes	Closed	Automatic
2. SH&G/ Detroit[a]	1000	H, HW	Yes	Closed	Manual
3. Barbash/ N. Y.[a]	440	H, HW	Yes	Open	Manual
4. Urban/ Chicago[a]	1000	H, HW	Yes	Closed	Automatic
5. MED House/ Calif.	500	H, HW, AC	Yes	Closed	Automatic
6. Perl Mack/ Denver[a]	500	H, HW, AC	Yes	Closed	Manual
7. CSU/ Ft. Collins[a]	500	H, HW	Yes	Closed	Manual
8. IBM/ Boulder[b]	165	Test	No.	?	None
9. Big Sur/ Calif.[b]	500	H, HW	Yes	Open	Manual

a. Retrofitted
b. Installed with Baseline Collector.

TABLE 3. SYSTEM DESIGN CHARACTERISTICS

Site	Relief Valve Configuration	City Water Top-Off	Control Algorithm	Freeze Protection	Heat Dump Mode	Collector Drain Approach	General
1. IGT/L.A.	— 30 psi PRV on each tank — 15 psi PRV on collector	Yes — Storage has system for automatic refill	— Pump controlled by thermocouple on collector	None	Yes — Can dump to atmosphere	Partial drain through valve on inlet	Have manual lockout on pump to prevent automatic refill
2. SH&G/Detroit	No PRV's on roof 30 psig PRV's on storage tanks	Yes — Manual	Pump on $\Delta T \geq 2°$ software control	Pump on 1 hr every 6 hr	Has four different heating and cooling loads	Partial drain inlet and outlet valves	
3. Barbash/N.Y.	— No PRV on roof — Tank open to atmosphere	Yes — Manual (?)	Pump turned on and off by clock	No details on freeze protection	Collector stagnation	Boilout	System open to atmosphere
4. Urban/Chicago	— 25 psi at each bank — 30 psi on storage tank	Yes — Automatic when press $\leq$ 12 psig and if power fails	— Pump runs 24 hr/day — Collector by-pass valve — Operated by photocell	— Full flow (since Dec) — Heat tape on piping	Can purge with city water	Partial drain through valve on inlet	— Had leak problem with orig. instal. by local craftsman — User would like to have drain capability
5. MED Houses/Mission Viejo, Calif.	— 25 psi PRV on roof — 25 psi on pump outlet	Yes — Refills below 10 psi	— Pump turned on and off with clock	None (piping is insulated)	Yes — Can dump to atmosphere	Partial drain	— System has run continuously but has overheated on several occasions, manifolds buckling and misaligned — Collector tilt — 19°
6. Perl Mack/Denver	— 30 psi PRV in attic — 30 psi PRV on storage tank — 30 psi PRV on pump outlet	Yes — Manual refill	— Pump on at 15 $Btu/hr\text{-}ft^2$ off at 8 $Btu/hr\text{-}ft^2$ — Computer control	Yes — Computer control if pump off 4 hr and $T \leq 37°F$, then pump on for 40 min	Collector stagnation	Boilout	
7. CSU/Ft. Collins	— 30 psi PRV on outlet of each row — 30 psi PRV on boiler	Yes — Manual refill	Pump controlled by analog system on collector ΔT (7.1°C)	Yes — Antifreeze in collector loop	Yes — Dual mode operation	Partial drain can open collector inlet and outlet to atmosphere	— Collector partially covered during installation and start-up — User would like to have drain capability — Had leaks during start-up
8. IBM/Boulder	?	Yes	Pump controlled by clock	Yes — Antifreeze in collector loop	N/A oversize storage tanks	?	— Original design allows collector purge with city water — Storage — 1000 gal tank — Collector — 165 ft^2

TABLE 3. (Concluded)

Site	Relief Valve Configuration	City Water Top-Off	Control Algorithm	Freeze Protection	Heat Dump Mode	Collector Drain Approach	General
9. Big Sur Calif.	— PRV at outlet of each bank — Air eliminators at each inlet	Yes — Manual refill	?	?	Yes — Can purge with city water	Partial drain can open collector inlet and outlet to atmosphere	— System start-up Dec 16 — Storage tank is 4000 gal lined redwood tank open to atmosphere
Totals	— PRV at collector/ 6 sites — PRV at tanks/ 5 sites — Atmospheric press/ 2 sites	— Automatic/ 3 systems — Manual/ 5 systems — None	— Clock control/ 3 systems — Collector $\Delta T/2$ systems — Intensity/ 3 systems	— Warm water purge/3 systems — Antifreeze/2 systems — None/2 systems	— Dump mode/ 5 systems — Dual mode/ 2 systems — Collector stagnation/2 systems	— Partial drain/ 6 systems — Boilout/2 systems	

Table 4 summarizes site experiences during start-up and operation of the systems. The topics addressed are important to determine if the glass breakage problem at each site was the result of collector design weaknesses or the improper application in a particular system. Site data logs were not kept, so the data were assembled from O-I reports and correspondence, and from telephone contact and site visits with designers and site personnel.

Boilout occurs when the collector is exposed to Sun while the fluid flow through the collector is stopped. The consequence is that the fluid changes to steam, increasing pressures to whatever level is required to escape from the system through relief valves or vent lines provided for overpressure protection. Boilout occurred 15 times, distributed across 6 of the 9 sites studied. Most instances of boilout occurred at sites 3 and 6 which also experienced frequent system malfunction due to experimentation with the controllers. Likewise, violent fracture of the glass collector tubes was only experienced at these two sites and this occurred on the second day of Sun exposure after a system malfunction. It was speculated that water remaining in the tubes after the first day's boilout would come to a boil on the second day and "percolate" fluid up the internal feeder tube to splash fluid onto dry parts of the inner surface of the collector tube which had reached stagnation temperatures as high as 650°F. O-I tests had shown that cooler fluid applied to the glass at stagnation temperatures would create a thermal shock causing the glass to fracture.

Hot fill is the condition where cool fluid enters a dry, or partially dry, collector which has been exposed to bright sunshine long enough for the inner absorber tube to reach stagnation temperature. Eleven instances of hot fill were identified and are shown in Table 4. These accounted for more than half of the total glass breakage problem. Owens-Illinois recognized the breakage risks due to hot fill and does not recommend filling the collector during bright Sun conditions.

It is to be expected that collector tubes may experience lengthy periods of dry stagnation temperatures during construction, or down time due to system malfunction and/or off-season operating modes. Among the systems evaluated, only 3 and 6 were designed to utilize dry stagnation as an operational mode. Others experienced brief periods of stagnation during construction before initial startup. These experiences, however, are not directly applicable since experience was with earlier collector configurations without reflectors and stagnation temperatures were not recorded. Sections IV and VI of this report discuss results of simulated stagnation conditions during MSFC solar simulator tests and O-I tests to assess the absorber coating stability at temperatures up to 700°F (371°C).

TABLE 4. SITE EXPERIENCES

Site	Boil-Offs	Hot Fills	Broken Tubes	Stagnation Exp.	Freeze-Ups	General
1. IGT/L.A.	July 1975 Jan 1976	None	4 — Aug 1975 1 — Jan 1976	Aug-Nov 1975	None	— 86 tubes changed due to vacuum loss — System malfunction Jan 1976
2. SH&G/Detroit	Yes — Date (?)	Yes — Date (?)		During start-up	Yes — Date (?)	— Freezing due to loss of vacuum and insufficient piping insulation — Had 8% tube replacement first year — 15 tubes with vacuum loss
3. Barbash/N.Y.	Dec 1975 Jan 1976 July 1976 Dec 1976	Unable to determine from reports	1 — Dec 1975 1 — July 1976 1 — Oct 1976 1 — Nov 1976	Aug-Sept 1976	Yes — Date (?)	— System malfunctions Dec 1975, Jan 1976, May 1976, July 1976, Oct-Nov 1976
4. Urban/Chicago	None	Oct 1976	4 — Oct 1976	System down from April-Oct 1976	Dec 1976 Jan 1977 (?)	— First freeze-up occurred with trickle flow when auxiliary heat failed — Second freeze-up occurred when PRV's froze
5. MED House/Mission Viejo, Calif.	None (system shows signs of having been overheated)	None	1 — Early start-up	None	None	— 17 tubes in bottom row show loss of vacuum (17/120) — Assume 34 total in two rows
6. Perl Mack/Denver	Sept 2, 3, 1976 Sept 17, 1976 Oct 13, 28, 30, 1976 Nov 7, 1976	Aug 30, 1976 Sept 2, 1976 Oct 25, 1976 Oct 28, 1976	1 — Aug 30, 1976 6 — Sept 3, 1976 3 — Sept 17, 1976 1 — Oct 13, 1976 1 — Oct 25, 1976 1 — Oct 28, 1976	None	None	— Approximately 10 system malfunctions due to controller — Controller changed about 6 times — 7 tubes with vacuum loss
7. CSU/Ft. Collins	Sept 30, 1976	Oct 9, 10, 1976 Oct 31, 1976	16 — Sept 30, 1976 18 — Oct 9, 10, 1976 7 — Oct 24, 31, 1976	?	Yes	— Manifold and piping froze — Most tube breakages occurred during start-up, boilout or refill
8. IBM/Boulder	None	Dec 10, 1976	1 — Dec 10, 1976	(?)	Yes — Nov 1976	— Freezing caused by low flow rate and poor insulation on 2 in. header pipe
9. Big Sur/Calif.	Dec 27, 1976	Dec 16, 1976	2 — Dec 16, 1976 3 — Dec 27, 1976	(?)	None	— Dec 27, 1976 owner tried to dump collector for tank repairs O-I instructed owner to empty collector
Totals for (9 sites)	15 boilouts	11 hot fills	74 broken tubes	Approximately 6 mo total exp.	6 freeze-ups	— 150 tubes vacuum loss — 6 freeze-ups — Approximately 18 system malfunctions of which approximately 15 were computer

Freeze-up of systems was experienced at 5 of the 9 sites surveyed, primarily the result of poor insulation on piping, valves, manifolds, and other system elements. The collector fluid at two locations had been changed to an antifreeze solution. Because freezing is heavily dependent on system design, it is necessary that a design "alert" be provided to the system designer to clearly state the requirement for adequate insulation, flow rates, antifreeze, or other protective means in system design and installation of the SUNPAK™ collector in low temperature locations.

The system survey primarily shows that system failures preceded, or accompanied, conditions of boilout, hot fill, and freeze-up that resulted in SUNPAK™ collector failure. As experience is gained O-I is providing guidelines, constraints, and applications engineering support to users of the collector. These precautions are expected to be a key element in future successful experience with systems using the SUNPAK™ collector.

IV. SOLAR SIMULATOR TESTS [3,5]

The solar simulator tests were planned to satisfy a multitude of objectives. Primarily it was desired to simulate the field conditions of the system where violent fracture of the glass tubes occurred. This was accomplished by circulating water through the collector until all air was removed. When the inlet and outlet were closed the only exit for the fluid in the collector was via a relief valve set at 30 psig and connected to the collector outlet by a 15-ft vent line. Secondly, it was desired to simulate maximum solar intensity expected in any location, or as a minimum to assure that dry collector tubes would reach a stagnation temperature greater than 600°F. Then, because violent glass fracture did not occur with boilout during the first day after system failure, each test of a set of collector tubes required 2 days of boilout. The first day merely established a water level for a partially filled collector at the beginning of the second day boilout period. Here, the objective was to confirm the O-I speculation that boiling water in a partially filled collector tube would "percolate" fluid onto dry parts of the collector which had reached stagnation temperature, thereby inducing violent fracture of the absorber tube. Finally, to characterize the collector temperature and pressure in each tube during boilout, complete instrumentation was required. Also, external failure characteristics and glass scatter were to be determined via video monitors focused on the collector area. Figure 4 shows the test configuration. The thin lexan cover over the collector was added to satisfy the MSFC Safety Office requirement to protect personnel and equipment from potential flying glass.

Four collector tube configurations were used for the simulator tests:

a) Good Regular Tubes — commercial collector tubes in "as received" condition. These were inspected to baseline drawings and proof tested to 350 psig.

b) Scratched Regular Tubes — regular collector tubes in which the interior of the absorber tube had been purposely scratched longitudinally in 12 places by O-I to assure fracture.

c) Good Slotted Tubes — specially fabricated tubes with an uncoated longitudinal strip through which the fluid could be observed for water level, boiling, and percolation action.

d) Scratched Slotted Tubes — slotted tubes which had been scratched as previously described.

For a given test, all 24 tubes in the collector were of the same configuration. Also, each 2-day boilout test began with a new set of tubes to avoid introduction of a fatigue factor.

Collector instrumentation consisted of 72 thermocouples, 3 in each tube, and 12 pressure transducers to sense pressure in the upper tubes. All measurements were coded as shown in Figure 5 and recorded on magnetic tape with the pressure measurements also fed to strip chart recorders for real time monitoring of potential pressure peaks. In addition, manual recording of temperature measurements at the manifold cups of tubes 6 through 12 was accomplished. Pressure guages and a flowmeter were provided for system fill and pressurization.

The omission of the coating in the slotted tubes results in a higher effective emittance for these tubes. Accordingly, the solar simulator was calibrated with regular and slotted tubes to determine the required intensity settings to simulate the same maximum net heat rate for both tube types. Based on the data shown in Figure 6, the simulator was adjusted [6] to provide 310 Btu/hr-ft^2 and

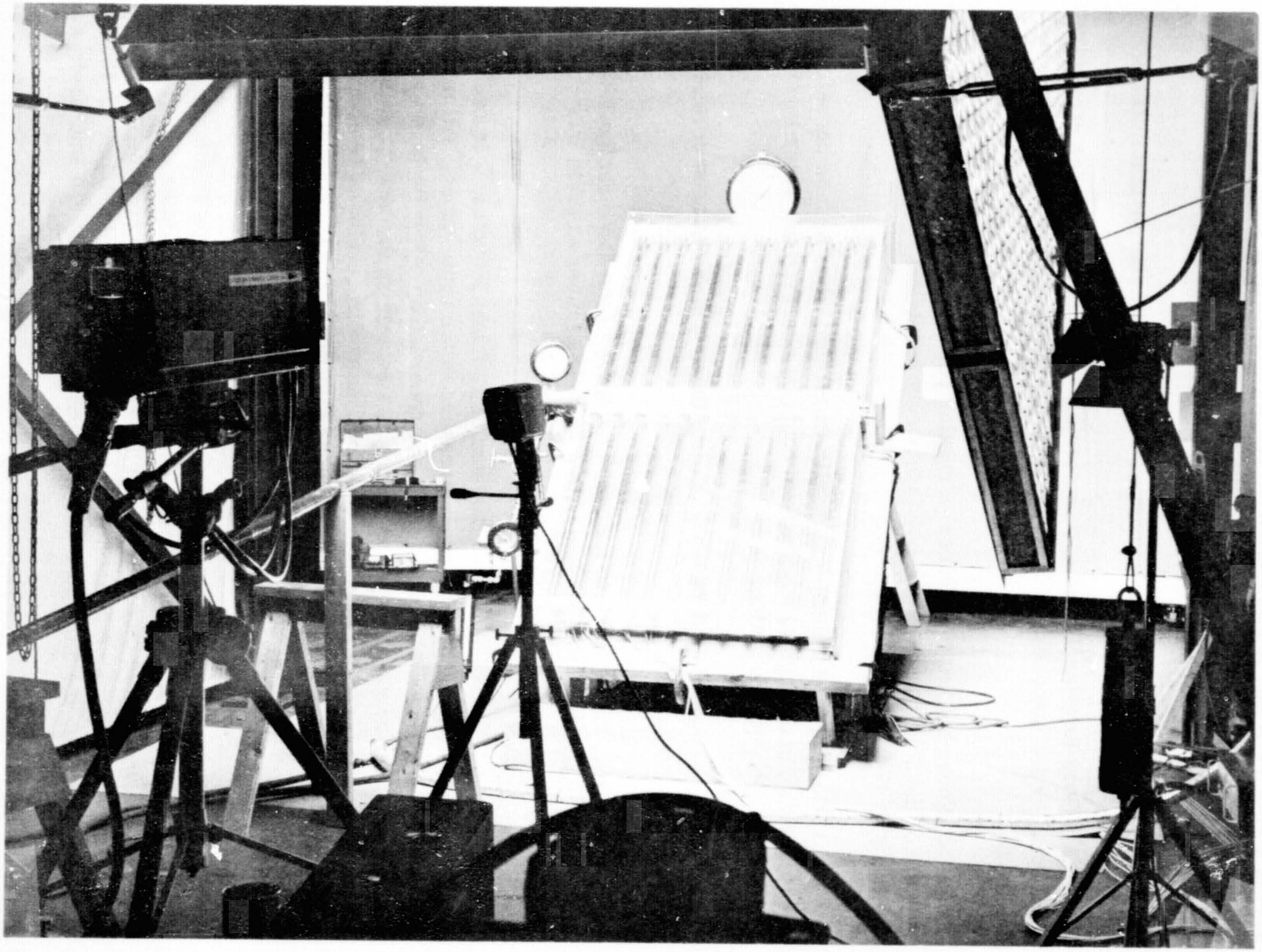

Figure 4. Test configuration.

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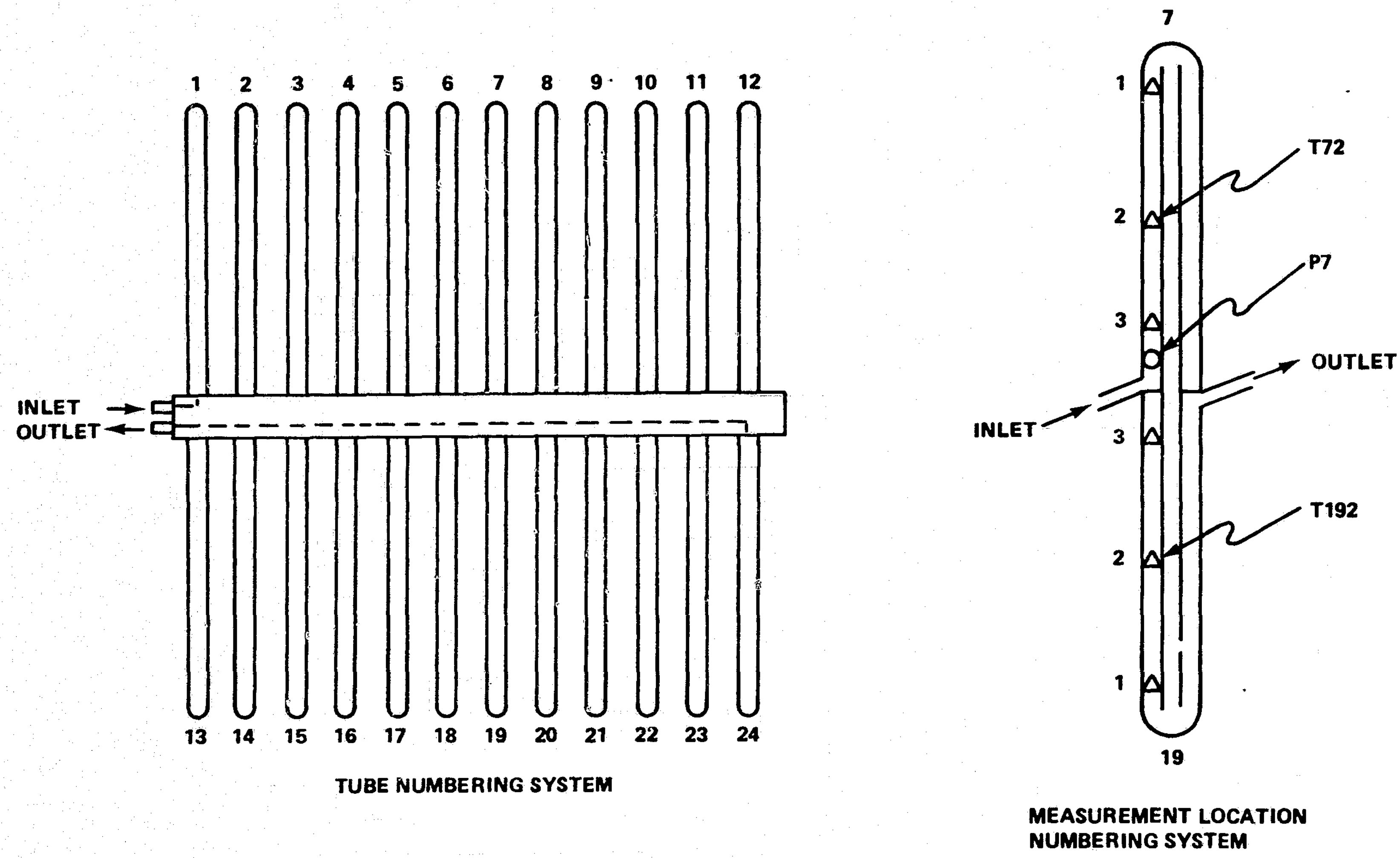

Figure 5. Collector instrumentation.

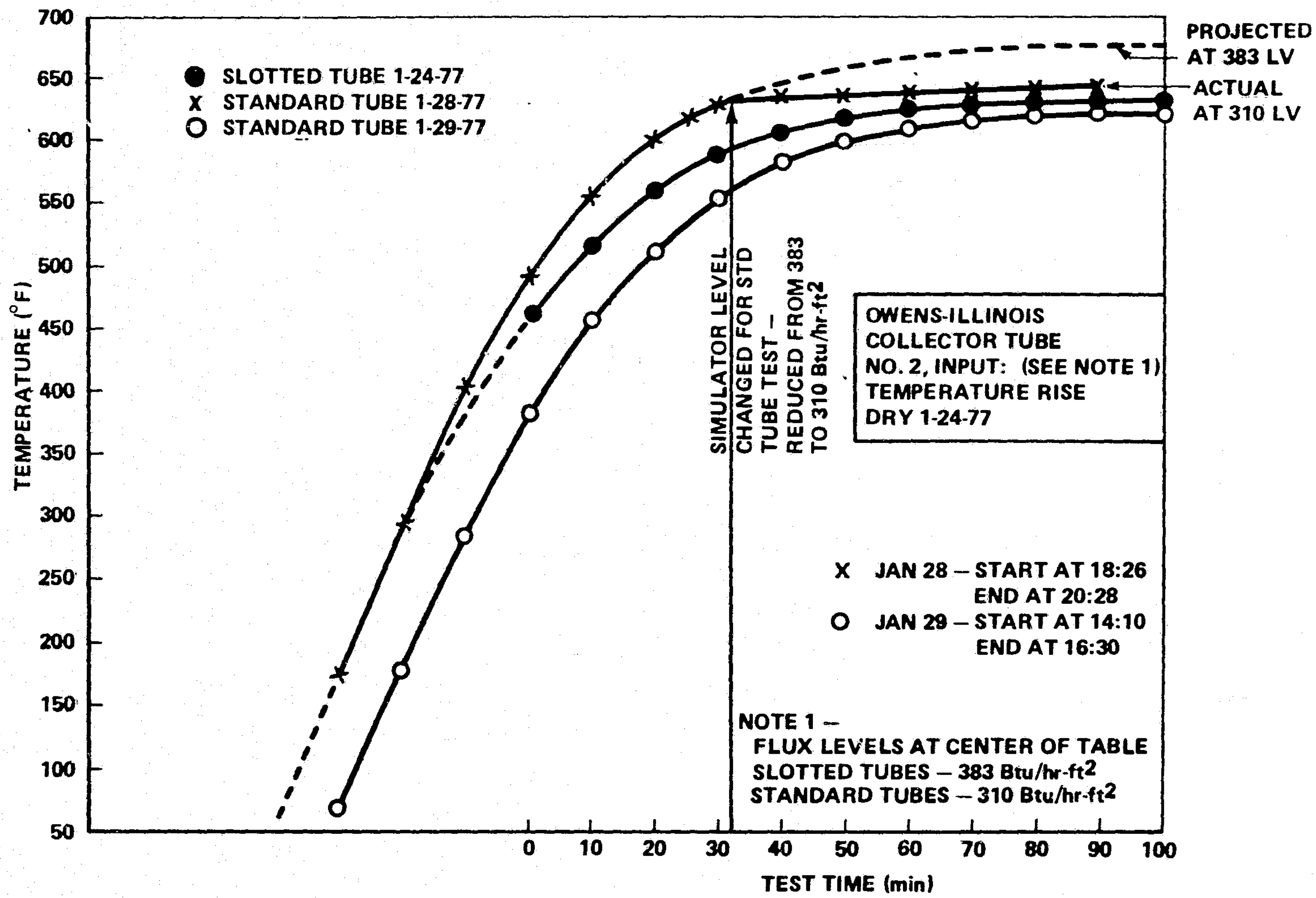

Figure 6. Solar simulator/tube calibration.

380 Btu/hr-ft^2 for regular and slotted tube tests, respectively. The data show typical temperature rise for both tube types illuminated at the calibrated levels. The rise rate reflects the predominance of a radiative heat transfer mode. Prior to any boilout test, each set of tubes installed in the test module was subjected to a dry stagnation test which consisted of illuminating the empty module at the proper intensity and verifying that each tube would have a minimum stagnation temperature above 600°F.

Each boilout test consisted of filling the collector with water, closing the inlet and outlet, pressurizing to 35 psia, and illumination by the solar simulator for 8 hr while allowing venting to take place at the 45 psia setting of the relief valve. Subsequent to an overnight cooldown, the collector was again heated by the simulator to simulate the second day boilout. During second day boilout simulations, numerous leaks occurred which resulted in early termination of all but one of the tests using good tubes. These leaks were the result of materials failures, primarily manifold solder and plastics, which are reported in Section VI. Table 5 lists the total series of tests conducted using the solar simulator.

Typical first day boilout temperature and pressure data are shown in Figures 7 and 8, respectively. After boiling and venting action began, the water level in each tube, as observed in tests of slotted tubes, fell to levels determined by pressure and temperature in each tube. Above the water levels, temperatures rose to stagnation levels as shown in Figure 7 after thermocouple T11 was uncovered. Figure 9 is a plot of the pressure gradient across the upper tubes with time as a parameter. Except for temperature variations in each tube due to coating differences and simulator illumination nonuniformity, the water level gradient, like pressure gradient, decreased uniformly from inlet to outlet tubes. During first day boilout, no unexpected thermodynamic phenomena were observed and no tube breakage occurred.

Following overnight cooldown, observation of the water level in the slotted tubes tested showed that steam condensing in the partially filled tubes created a vacuum to cause complete water backfilling of the tubes toward the inlet side of the collector with water remaining in the collector. The remaining tubes toward the outlet of the collector were drained except for a small residual quantity of water below the feeder tubes. This water was left when the vacuum seal between the water and feeder tube was broken as backfilling progressed.

TABLE 5. SUNPAK™ COLLECTOR TESTS ON MSFC SOLAR SIMULATOR

Jan 24 (383 Btu/hr-ft^2)	Calibration of slotted tubes
Jan 27 (383 Btu/hr-ft^2)	Slotted tube boilout — first day Leaks at Nos. 18, 23, 24 tubes — manifold misaligned
Jan 28 (310 Btu/hr-ft^2)	Calibration of standard tubes — set A
Jan 29 (310 Btu/hr-ft^2)	Calibration of standard tubes — set B
. . . . . Replaced manifold	
Feb 4 (383 Btu/hr-ft^2)	Slotted tube boilout — first day 8 hr — leak at first tube after shutdown
Feb 7 (383 Btu/hr-ft^2)	Slotted tube boilout — first day Boiled out about 2/3 of water
Feb 8 (383 Btu/hr-ft^2)	Slotted tube boilout — second day
Feb 9 (305 Btu/hr-ft^2)	"A" standard tube boilout — first day (Inlet valve leak; refilled collector)
Feb 10 (310 Btu/hr-ft^2)	"A" standard tube boilout — first day (repeat)
Feb 11 (380 Btu/hr-ft^2)	"A" standard tube boilout — second day 1:15 pm — tubes 8, 9, and 10/manifold leak — manifold solder

TABLE 5. (Concluded)

..... Replaced manifold (silver soldered)	
Feb 25 ($310\ Btu/hr\text{-}ft^2$)	"B" standard tube boilout — first day Leak due to end cap deformation
Feb 28 ($310\ Btu/hr\text{-}ft^2$)	"B" standard tube boilout — first day Boiled out 2/3 of water
Mar 1 ($380\ Btu/hr\text{-}ft^2$)	"B" standard tube boilout — second day Manifold header cap leaked — solder melted
Mar 3 ($415\ Btu/hr\text{-}ft^2$)	"C" slotted scratched tube boilout — first day Boiled out 3/4 of water (hotter simulator)
Mar 4 ($383\ Btu/hr\text{-}ft^2$)	"C" slotted scratched tube boilout — second day Violent fractures — Nos. 7, 9, and 16 Secondary breaks — Nos. 17 and 24 Passive ring-off — No. 4
Mar 8 ($310\ Btu/hr\text{-}ft^2$)	"D" standard scratched tube boilout — first day Boiled out 2/3 of water
Mar 9 ($380\ Btu/hr\text{-}ft^2$)	"D" standard scratched tube boilout — second day Violent fractures — Nos. 5 and 23 Passive ring-off — Nos. 12, 22, 20, and 19
Mar 11 ($380\ Btu/hr\text{-}ft^2$)	Irvine School slotted tubes boilout — first day Boiled out 23 tubes
Mar 12 ($380\ Btu/hr\text{-}ft^2$)	Irvine School slotted tubes boilout — second day Boiled out till leak dropped pressures; no breaks during vent; heat set in end cap
Mar 12 ($380\ Btu/hr\text{-}ft^2$)	Irvine School hot fill (600 to 650°F) Shatter No. 1 tube when water reached 40 percent level

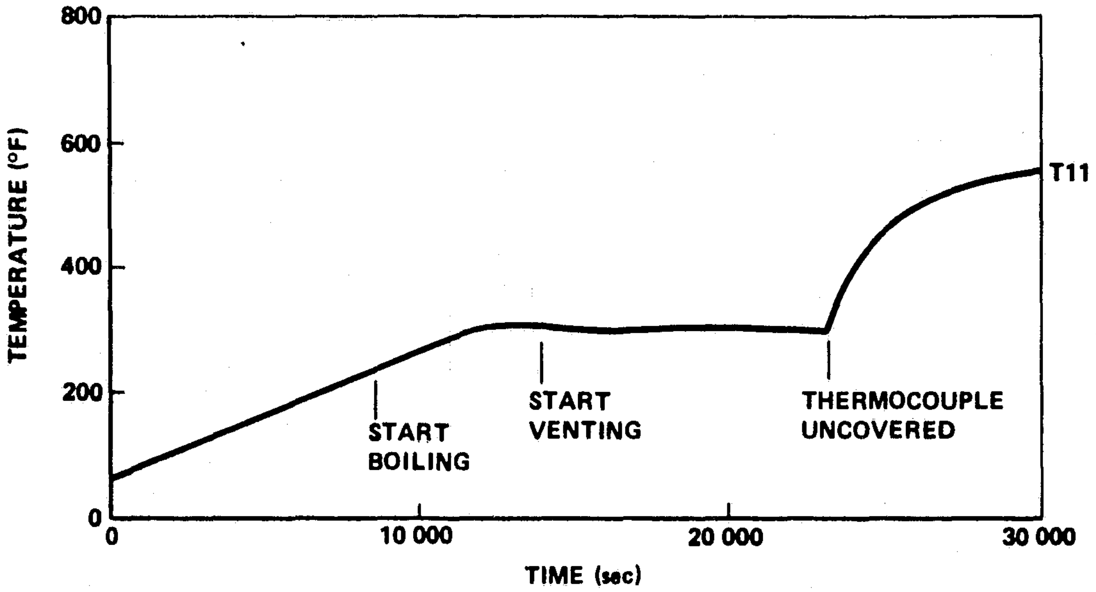

Figure 7. Temperature history for a typical first day boilout.

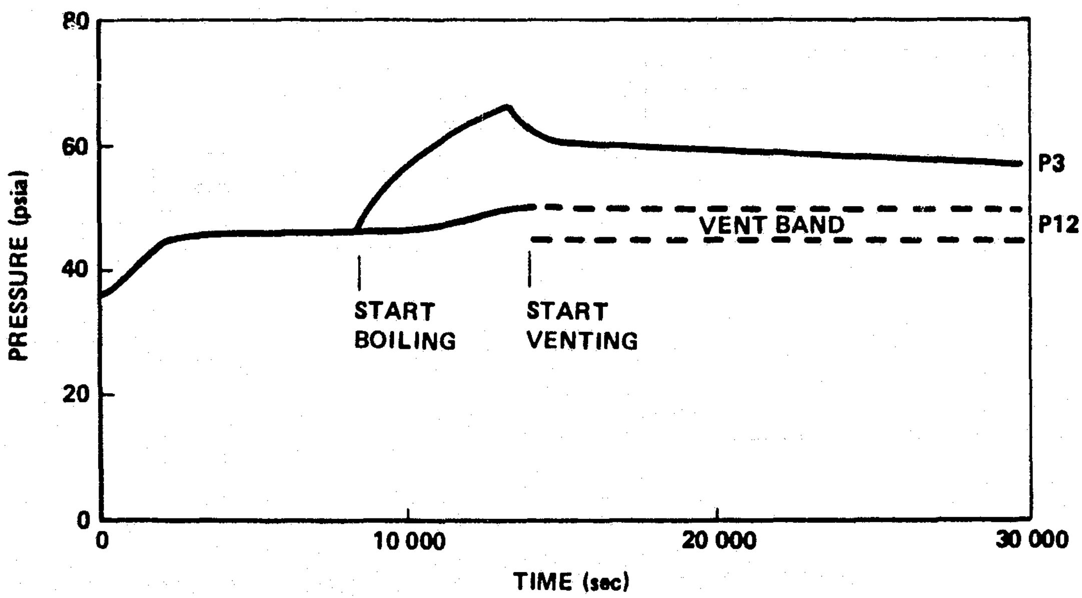

Figure 8. Pressure history for a typical first day boilout.

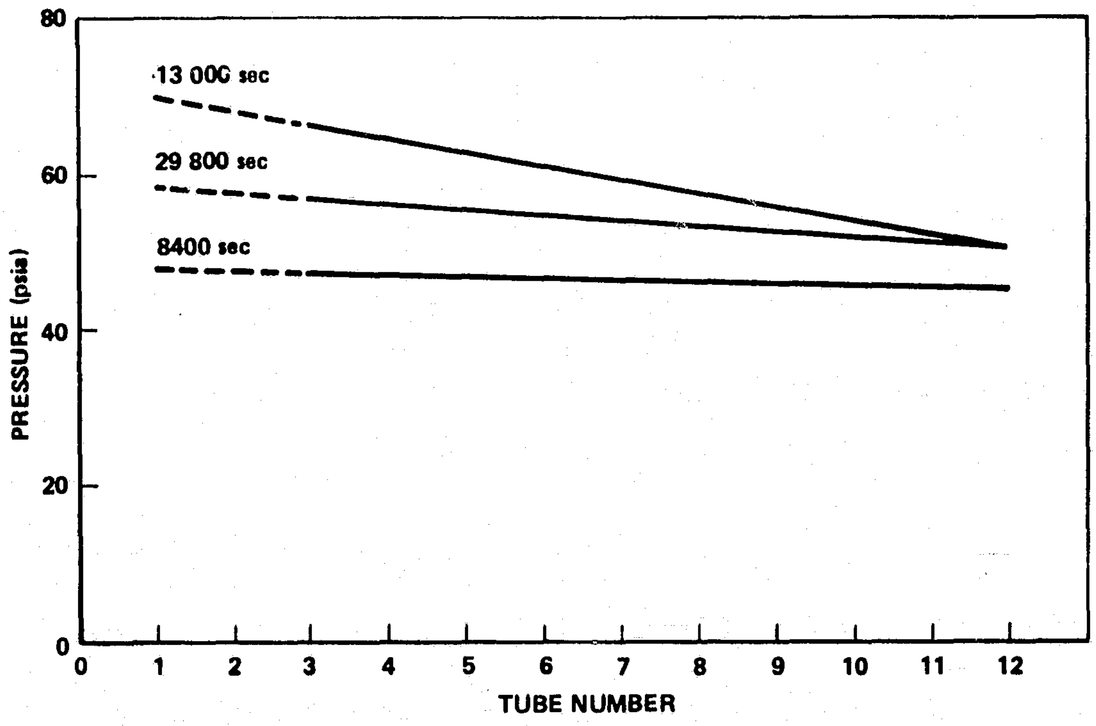

Figure 9. Pressure profile for collector tubes during a first day boilout.

Figures 10, 11, and 12 show typical data from second day boilout tests. From the character of the pressure gradient in Figure 10, one can conclude that water had backfilled tubes 1 through 5 leaving tubes 6 through 12 empty prior to start of second day boilout. This was observed in tests with slotted tubes as well as the fact that venting after boilout began did not redistribute water from the full tubes to the empty tubes. Hence, the percolating of boiling water does not occur to cause thermal shock and violent fracture of the absorber tube. Also, Figure 11 shows no glass breaking pressure surge when venting begins as one might expect if water were to move from a full tube into an empty tube which had reached stagnation temperature before the initial vent. Figure 12 shows there was not sufficient water in the collector after the first day boilout to completely backfill tube No. 5. Temperature at this upper thermocouple reached stagnation before the first vent occurred where the temperature at the same location in the full No. 1 tube was that of the boiling water. At the first vent, the stagnant portion of the partially full tube is cooled slowly, again indicating no large transfer of water onto the hot surface. During all second day boilout tests with good tubes, unexpected thermodynamic phenomena were not observed and no tubes broke. Hence, one can conclude that good tubes will safely withstand the simulated boilout conditions.

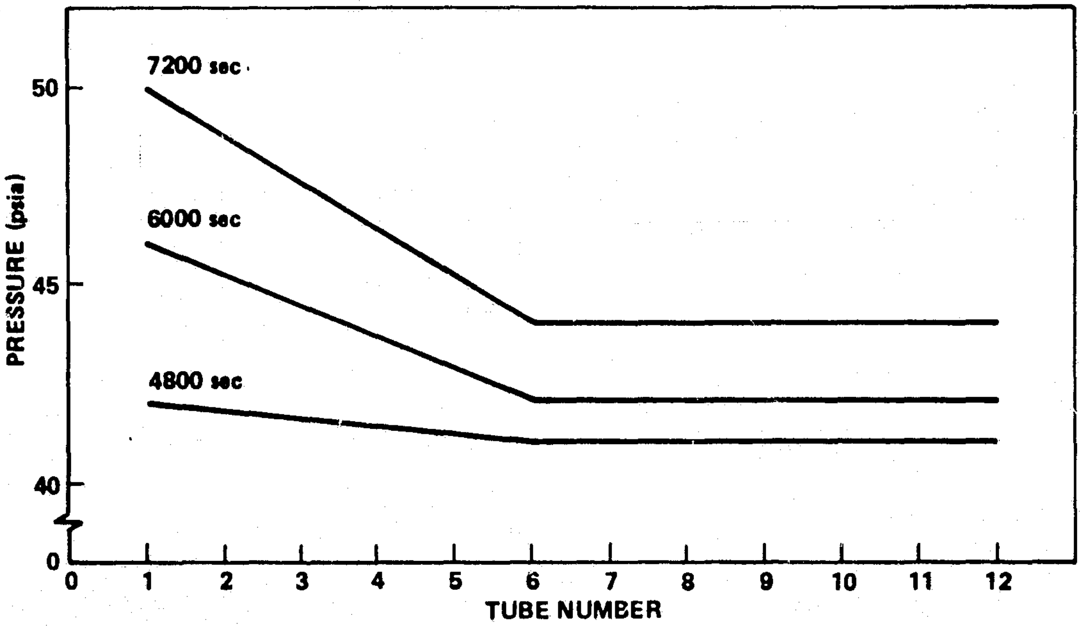

Figure 10. Pressure profile for collector tubes during a typical second day boilout.

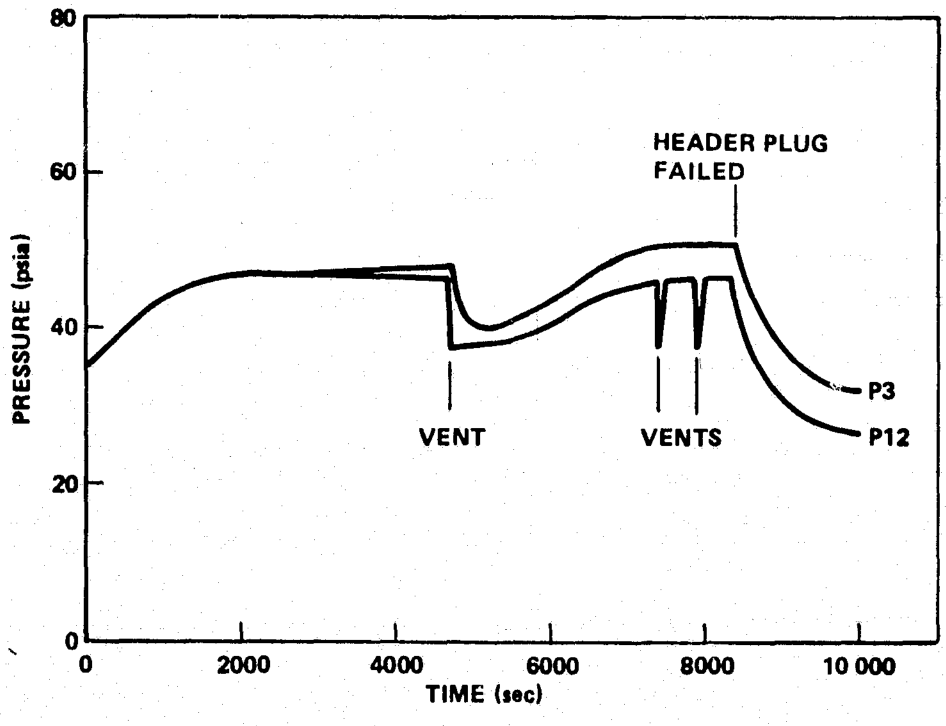

Figure 11. Pressure history for a typical second day boilout.

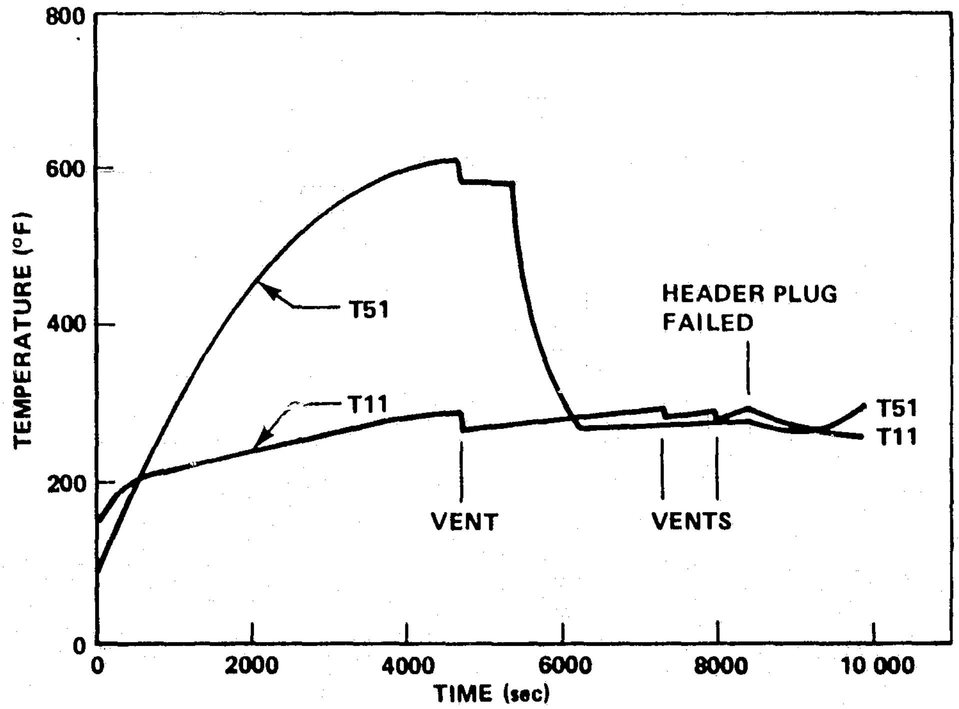

Figure 12. Temperature history for a typical second day boilout.

The conditions which resulted in failure of the manifold solder can be understood from the temperature data shown in Figure 13 for tube cup 12 which is near the soldered manifold header plug that leaked in a second day boilout test. As venting begins, the temperature of steam passing through empty tubes at stagnation temperature begins a rapid rise. This temperature rise of steam is then similarly transferred to the copper manifold elements which interconnect the tubes. The time at which the melting point of solder is reached and failure occurred is shown. Figure 14 compares temperature of cup 8 to temperatures of the tubes upstream and downstream of the cup. The tube temperatures are those sensed by thermocouples located nearest the manifold.

Since violent fracture of good tubes did not occur during boilout tests in the MSFC solar simulator or in the array tested by O-I at Andover, Massachusetts, scratched tubes were substituted in the array to force tube failure. After O-I determined the scratch pattern which would assure failure, two sets of tubes were provided to MSFC for boilout tests with the solar simulator. Both sets of tubes withstood first day boilout. During second day boilout,

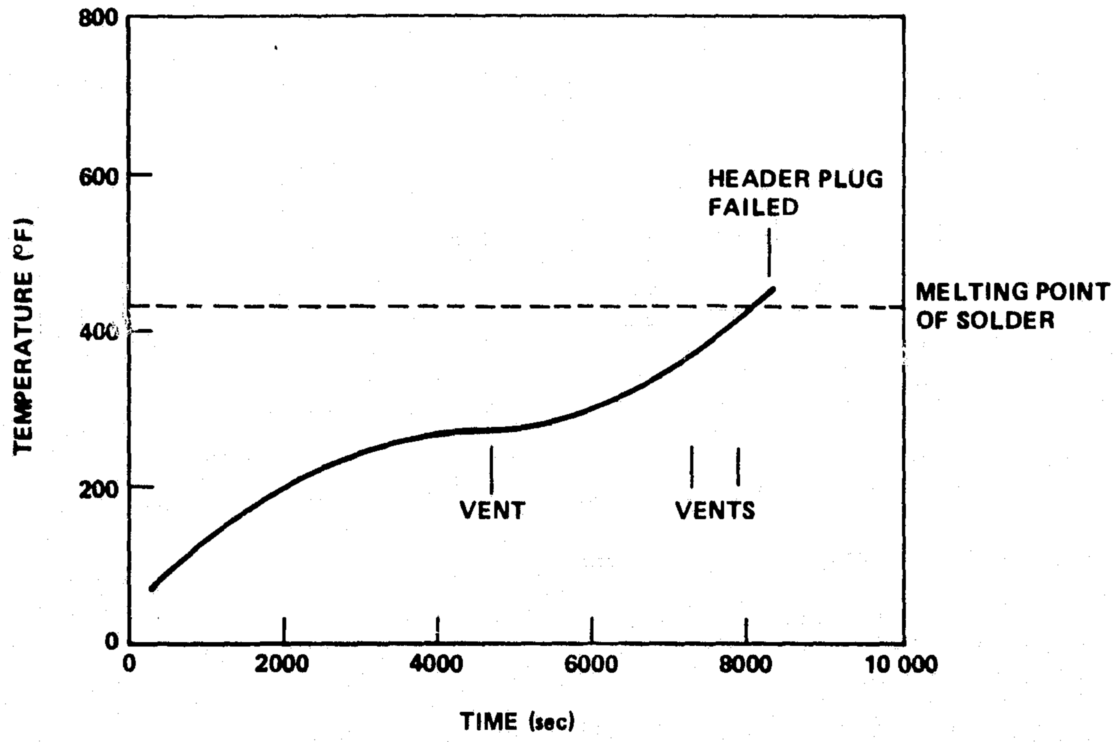

Figure 13. Temperature history of cup 12 for header plug failure.

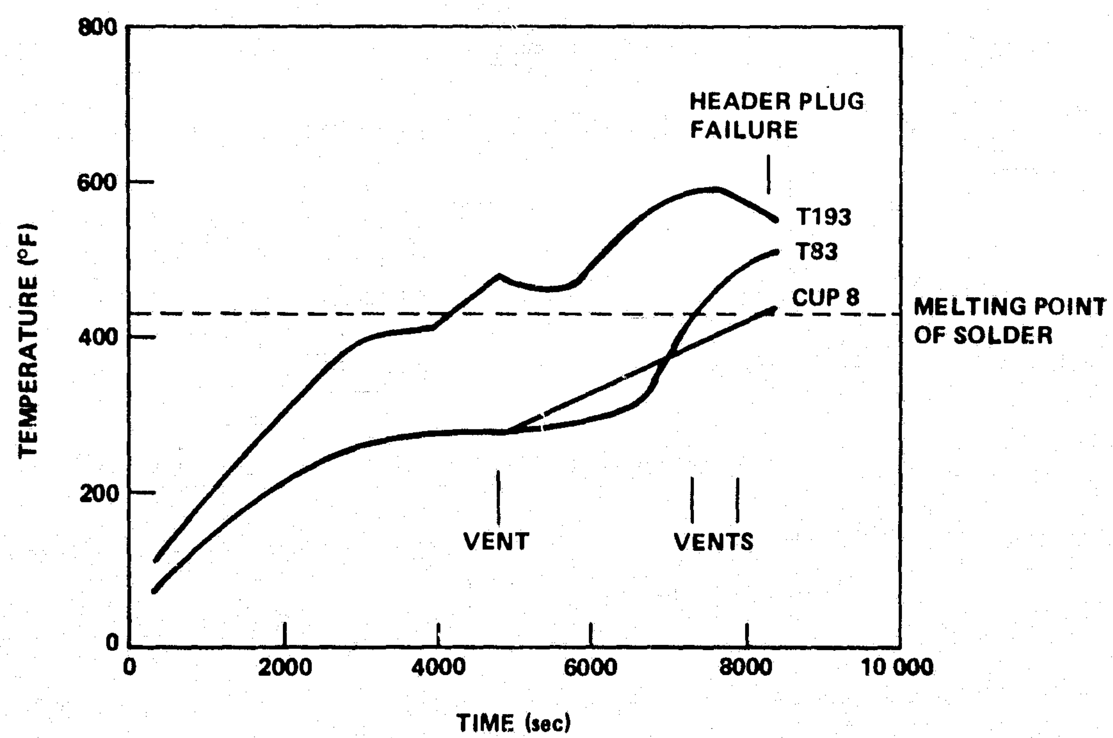

Figure 14. Temperature history of gradients through manifold for header plug failure.

however, violent fracture of several tubes in each set occurred. In neither test was there any indication in the data that tube breakage was imminent. It should be noted that the breakage occurred at approximately the time boiling began, but before the first vent of the relief valve.

Figures 15, 16, and 17 show the failed condition of the first set of scratched tubes after the collector had cooled to permit safe inspection. Violent fracture had occurred in tubes 16, 7, and 9; tubes 17 and 24 suffered secondary breaks from flying glass; and tube 4 had a passive ring-off in the inner absorber tube. The feeder tube is seen separated at the joint in tube 16 which fractured first. The rubber material used for this joint and tip protectors on the feeder tubes had been observed to soften and become putty-like after being subjected to temperatures of a second day boilout. It is not known if this separation resulted from the violent fracture, or caused the fracture by allowing the feeder tube to touch residual water which could then percolate up the tube to splash on the hot absorber tube. Pressure sensed at either side of the failed tube 16 is shown in Figure 18 and indicates no pressure surge before failure. Similarly, the temperature histories (Figs. 19, 20, and 21) for the failed tube and tubes either side of the failure indicate a stable condition at the time of failure.

Figure 22 shows the failed condition of the second set of scratched tubes. Tubes 5 and 23 experienced violent fracture as shown in Figures 23 and 24, respectively. It is noted that the feeder tube connection remained intact even though tube 23 suffered violent fracture. Passive ring-off breaks in absorber tubes 12, 19, 20, and 22 also occurred during failure of the second set of scratched tubes, as seen in Figure 25, by the condensation inside the affected tubes.

One final test was accomplished to simulate a "hot fill" condition. The collector was fitted with a good set of slotted tubes and illuminated by the solar simulator until stagnation temperature was reached. The tubes were dry and the collector outlet open to atmosphere pressure only. Then slow filling of the collector with warm tap water was begun. Tube 1 broke after being filled to approximately 40 percent capacity (Fig. 26). The collector was not pressurized during this test; therefore, the glass dispersion was less than when violent fracture occurred during the scratched tube boilout tests.

Since the operating pressure of the SUNPAK™ collector remained well below the burst pressure of the tubes and no pressure spikes were observed during simulated boilout tests, one can conclude that glass fracture occurs as a

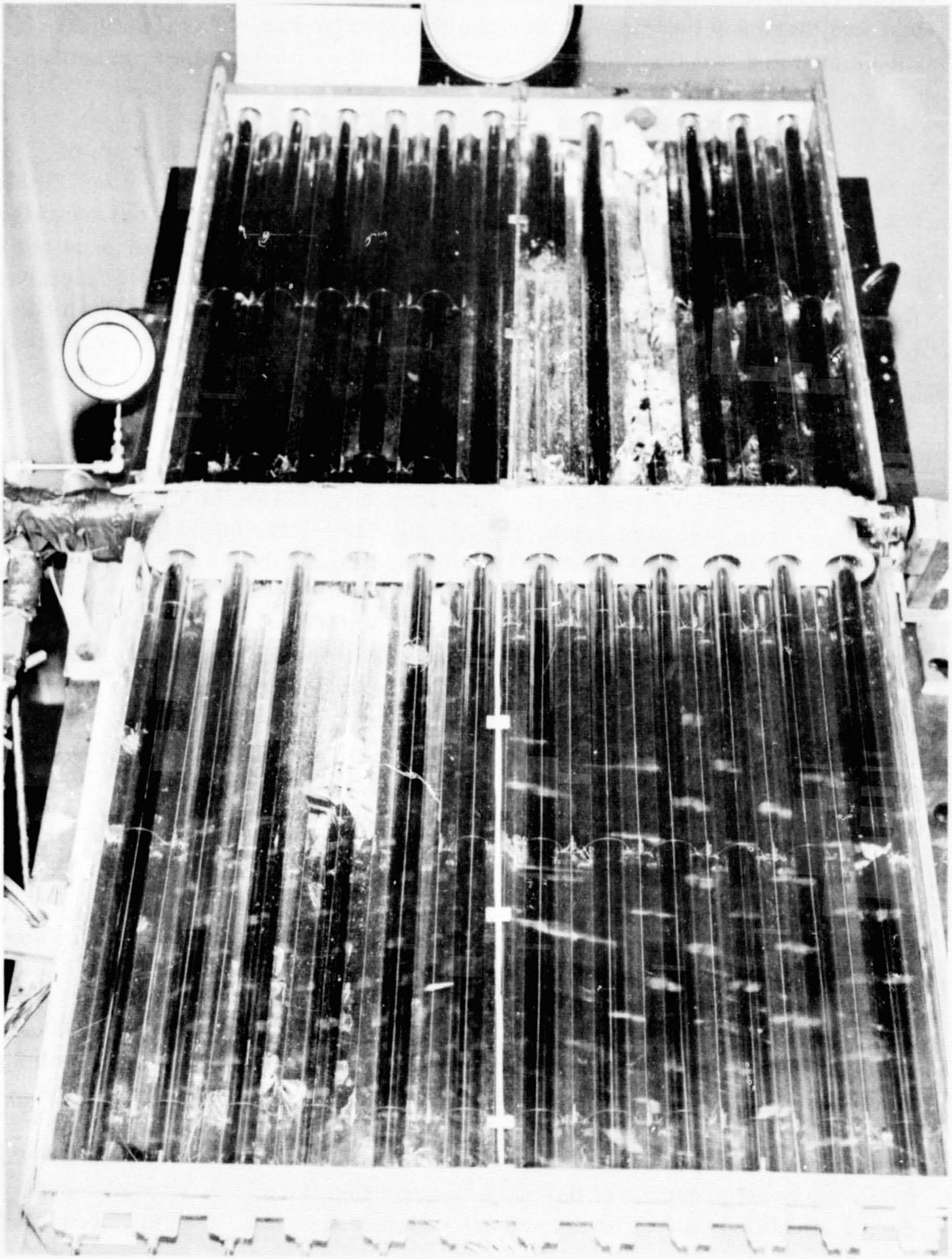

Figure 15. First failure with scratched tubes.

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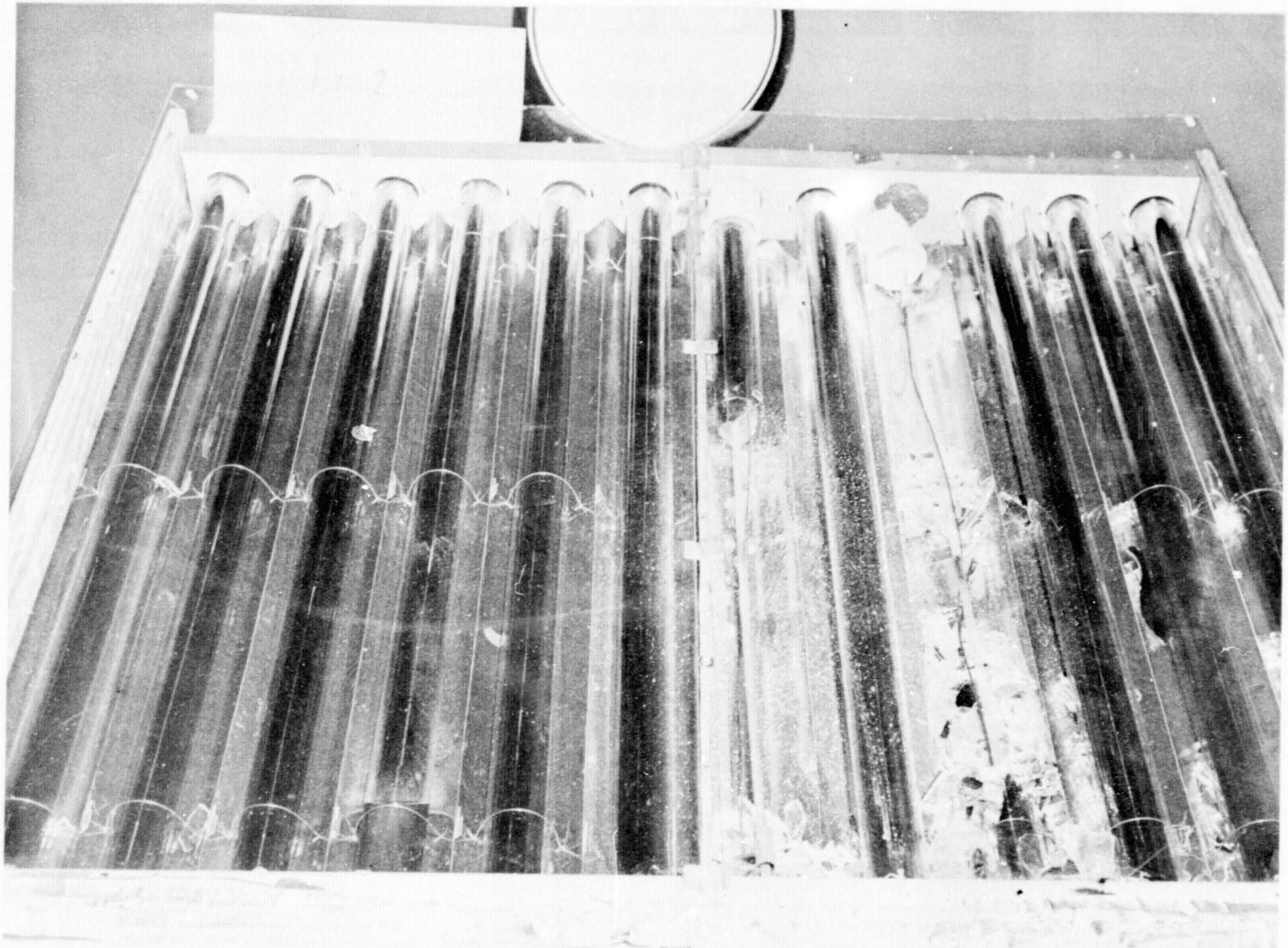

Figure 16. Failed upper tubes.

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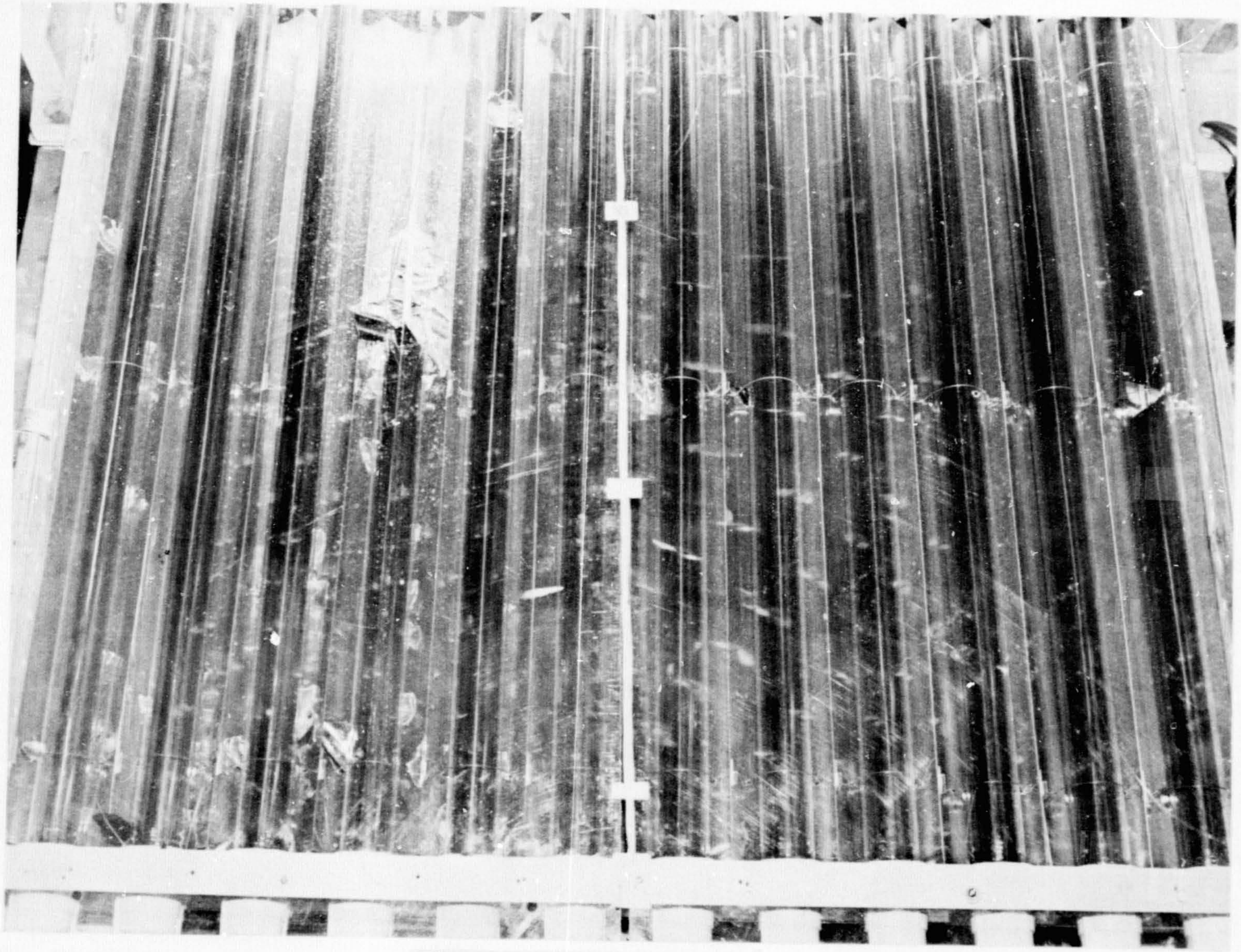

Figure 17. Failed lower tubes.

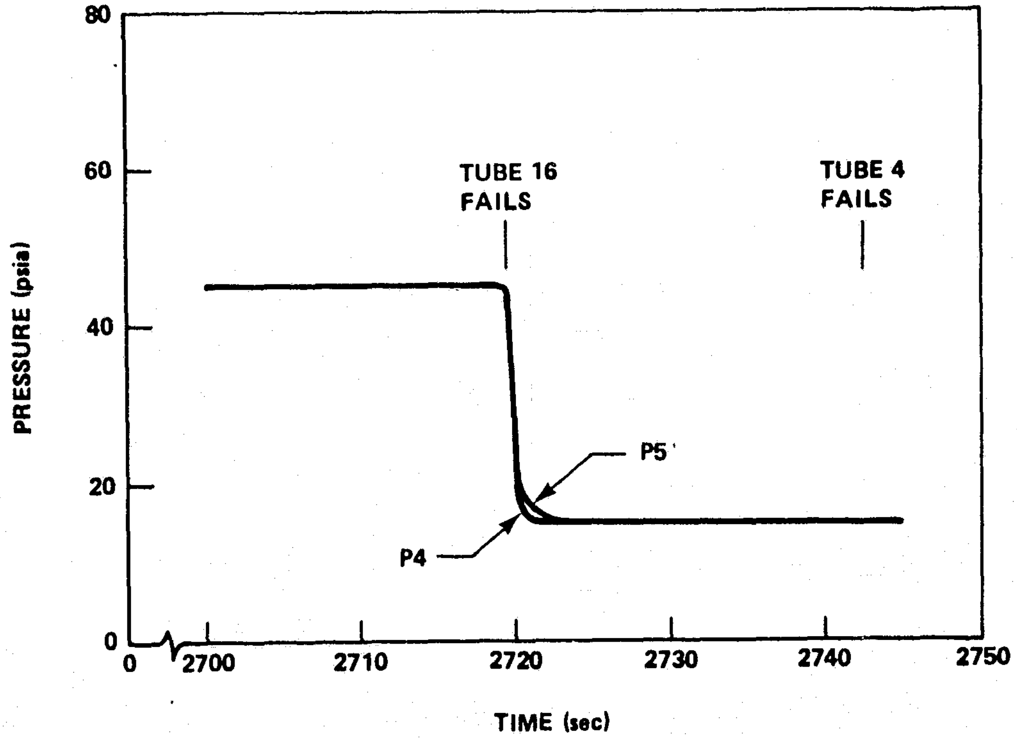

Figure 18. Pressure history when tube 16 failed.

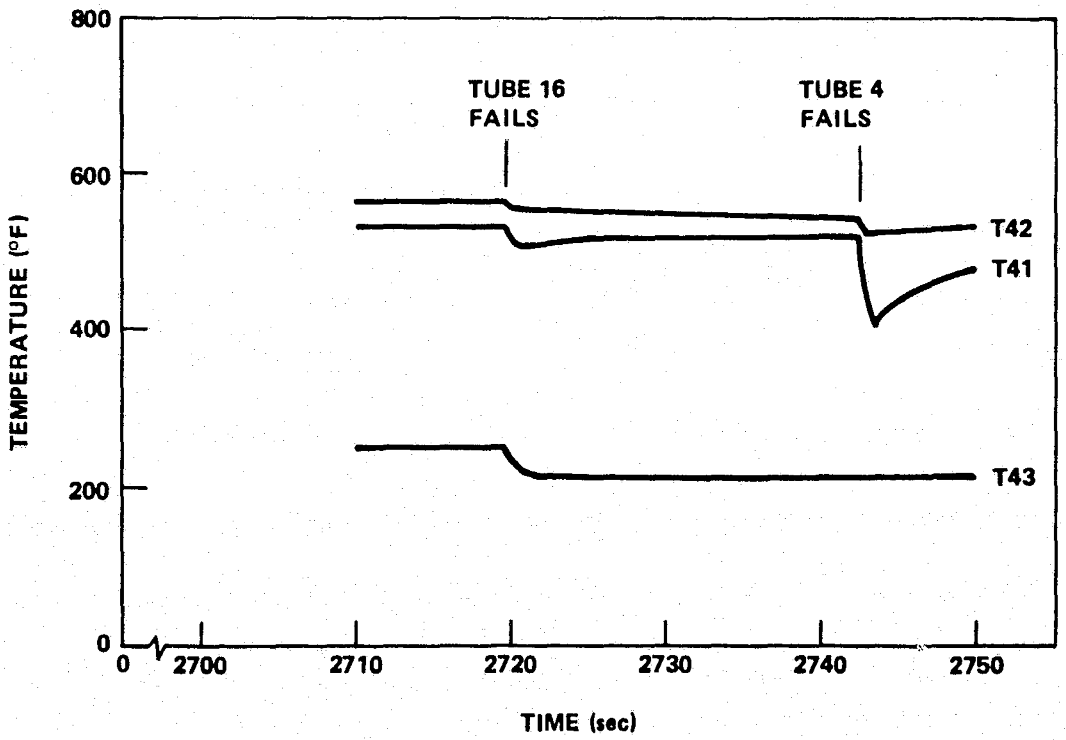

Figure 19. Temperature history for tube 4 when tube 16 failed.

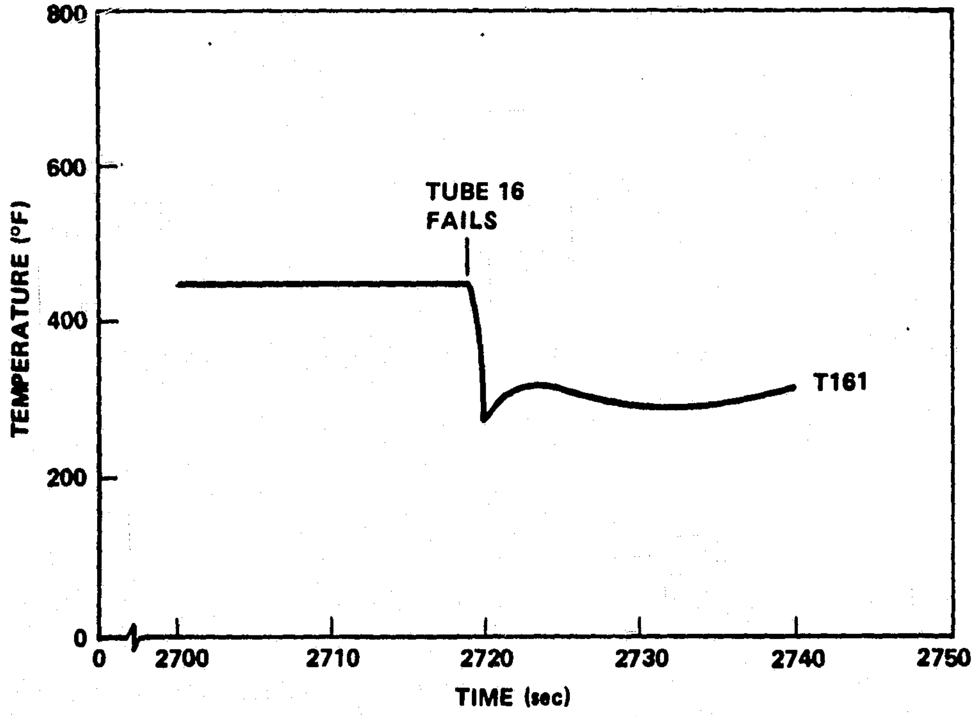

Figure 20. Temperature history for tube 16 at failure.

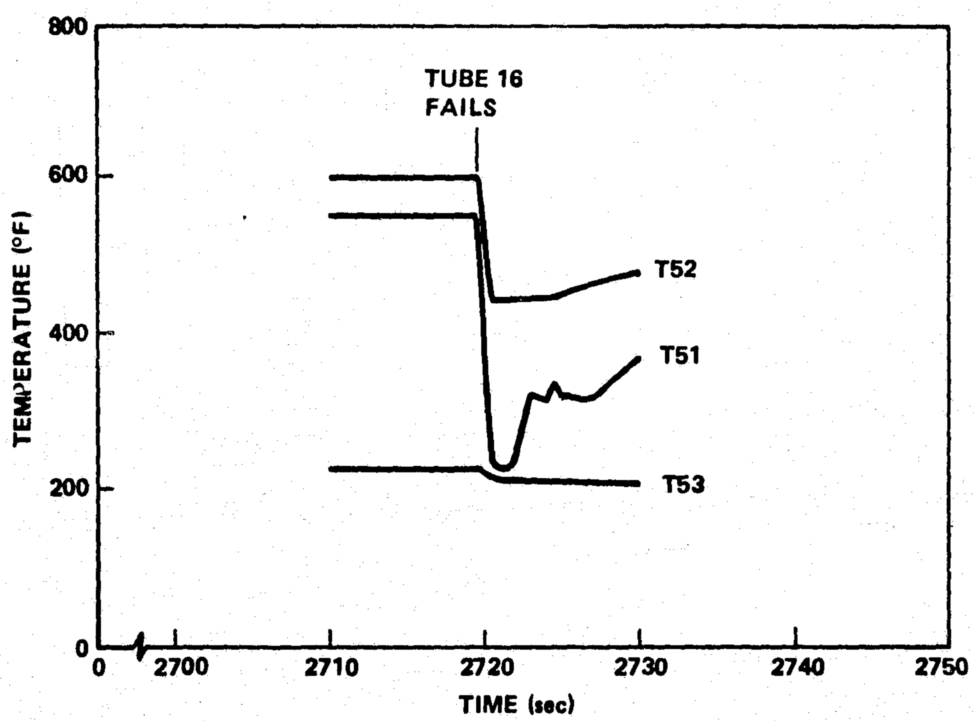

Figure 21. Temperature history for tube 5 when tube 16 failed.

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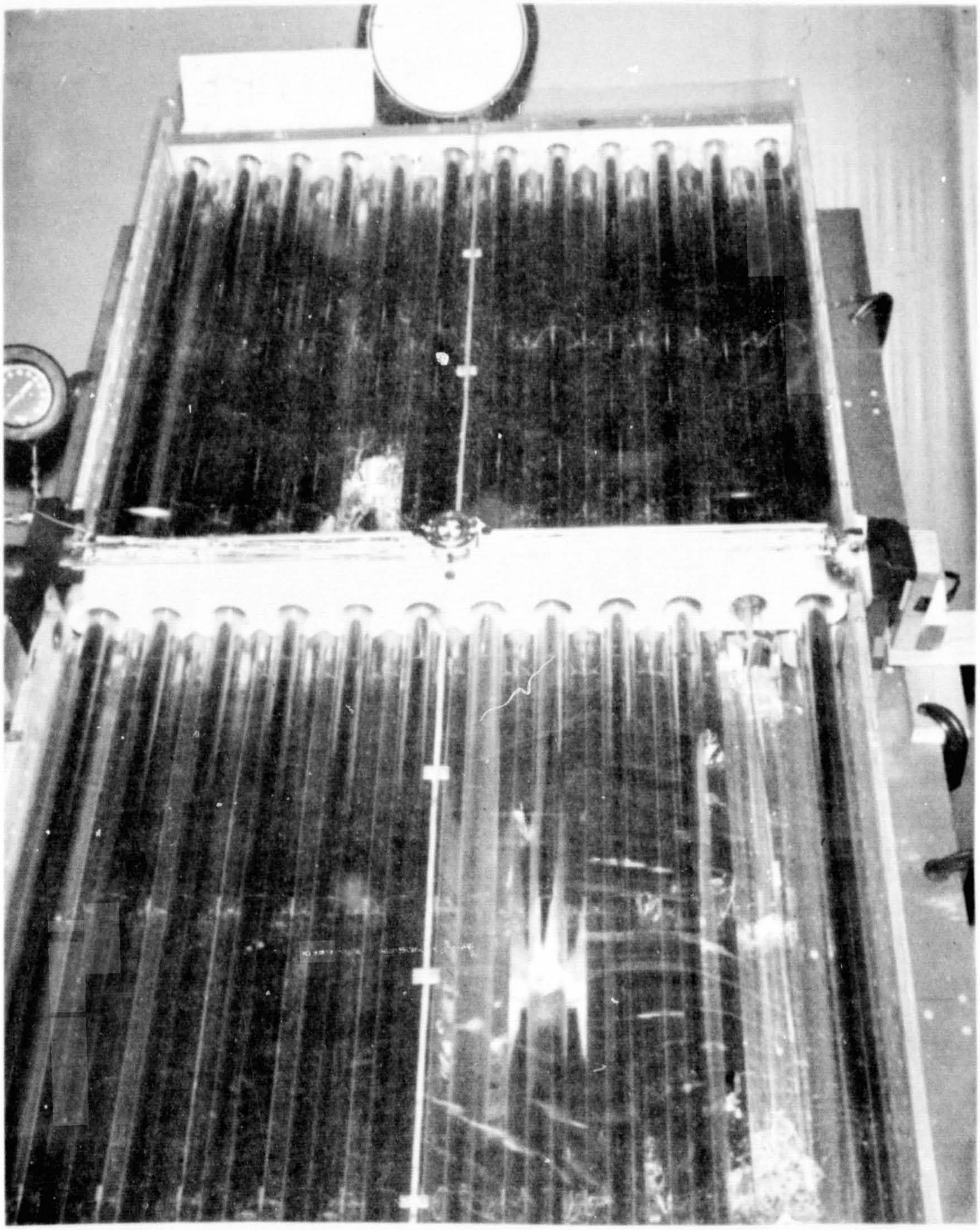

Figure 22. Second failure with scratched tubes.

Figure 23. Tube 5 after violent fracture.

Figure 24. Tube 23 after violent fracture.

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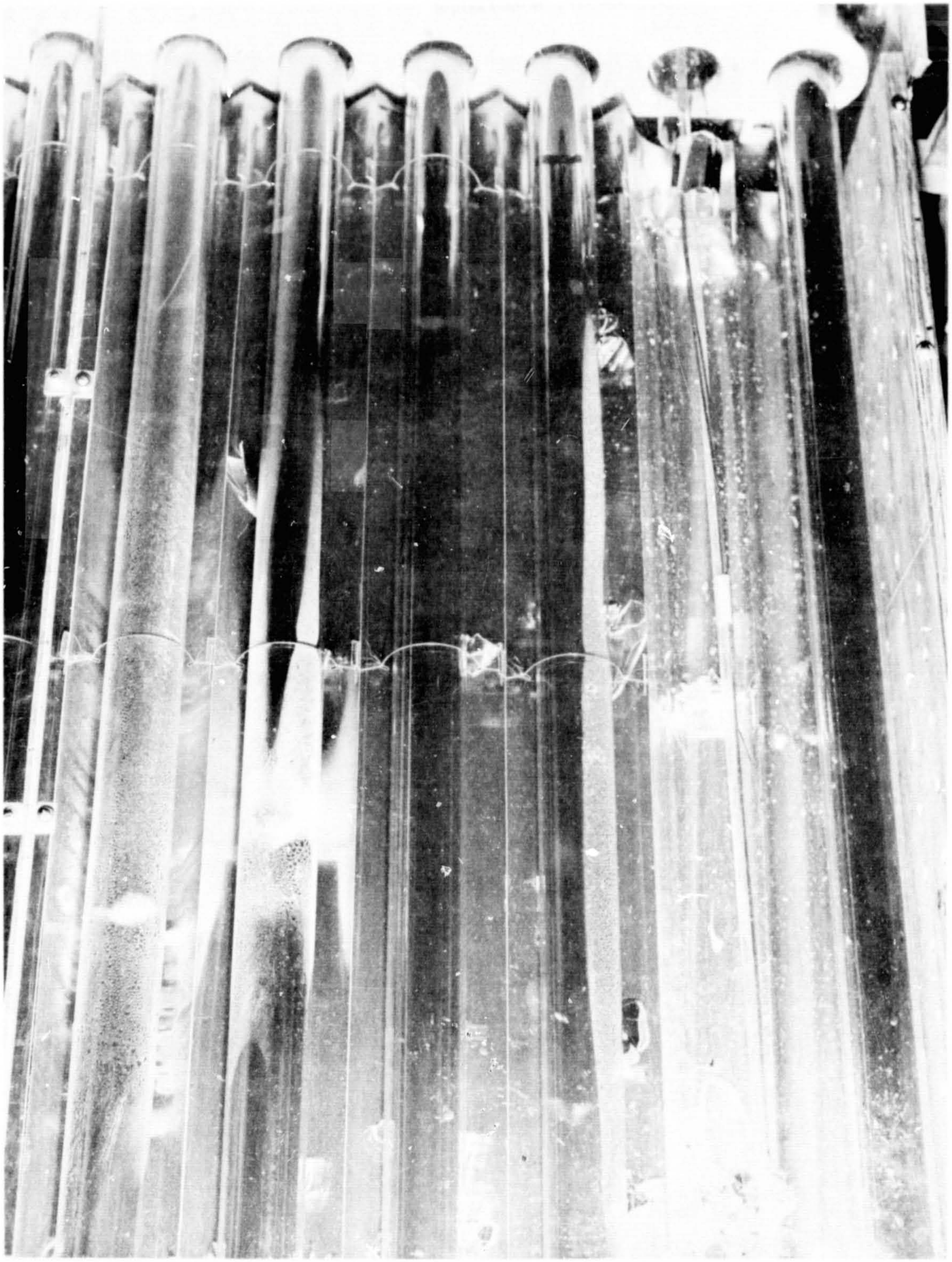

Figure 25. Ring-off breaks in absorber tubes.

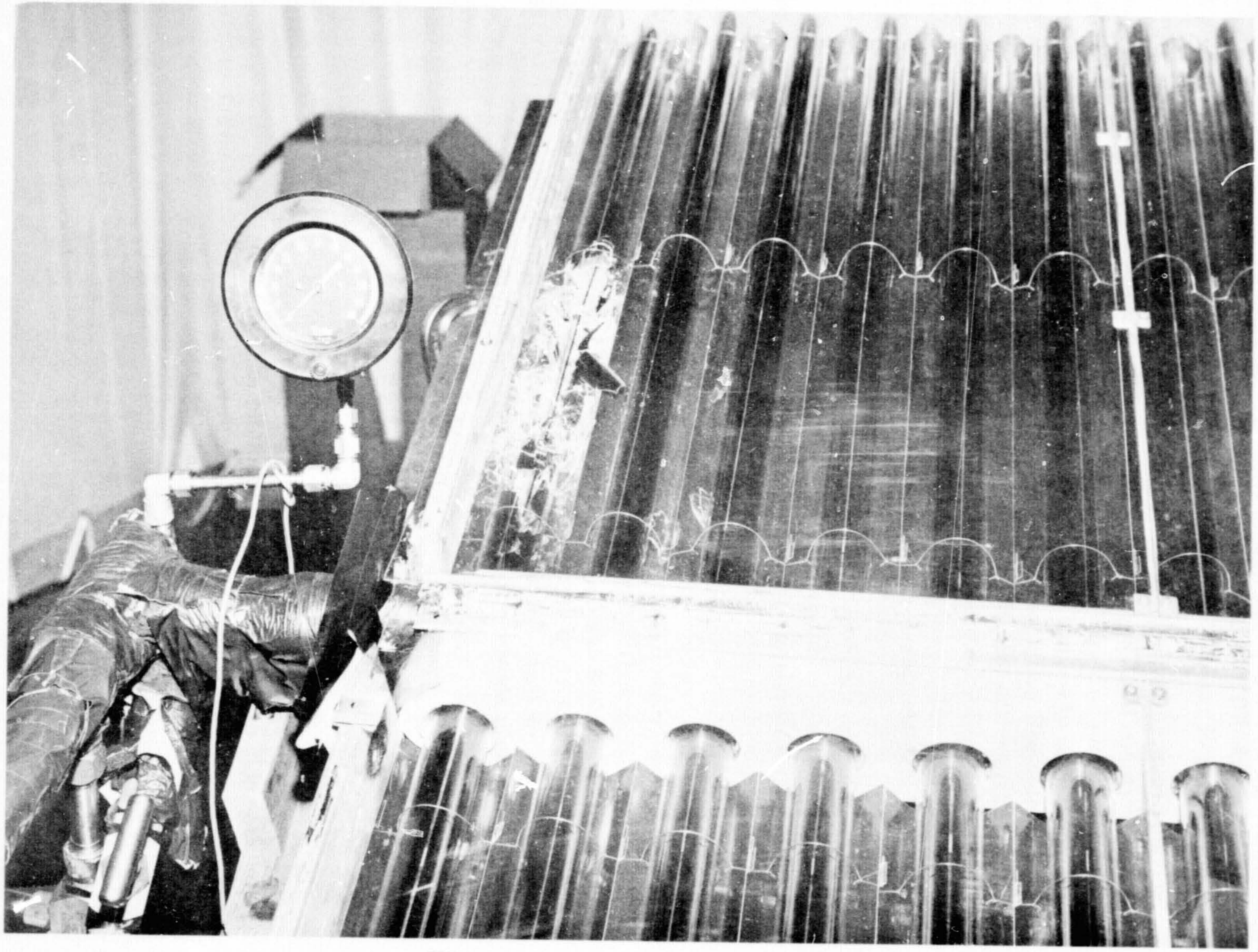

Figure 26. Hot-fill tube failure.

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result of thermally induced stresses combined with the static pressure stress. Four possible sources of thermally induced stresses have been identified. These are hot-fill, percolation of water through a disconnected lower feeder tube, boiling of residual water in the lower tubes, and fluid flow as a result of sudden pressure loss. Users of the SUNPAK^{TM} collector can avoid hot-fill glass fractures by filling the collector only when it is cool. Separation of the feeder tube can be avoided by assembling the feeder tube so the coupling is on the upper side of the manifold. In this location, the weight of the short feeder tube section will act to retain the joint rather than separate it. Finally, systems can be designed so that backfill during cooldown after a first day boilout will result in all collector tubes being filled with water at the start of a second day boilout. This will avoid potential fluid flow into hot empty tubes if a sudden pressure loss should occur.

Although the solar simulator testing of the SUNPAK^{TM} collector assembled with good tubes indicates that first and second day boilout can be accomplished without glass fracture, this should be prevented by system design considerations like city water top-off or other schemes to assure continuous fluid flow through the collector when a malfunction occurs. The weak link at the time of this assessment was the low temperature capability of the manifold solder and the rubber material used for feeder tube couplings and tip protectors. It was also observed that the plastic used for the tube support cup inserts softened or cracked during prolonged exposure to the solar simulator heat levels. This failure is seen in Figure 27 and is reported because it was a major cause for leaks during the boilout tests. Recommendations to improve these materials shortcomings are discussed in Section VI.

V. DESIGN EVALUATION [3, 7]

Two areas of the SUNPAK^{TM} collector design were reviewed to investigate possible causes for the tubes breaking. One was the alignment tolerances for assembly of the tubes into the manifold and the other concerned a strength analysis of the collector tube itself. A third area, related to leakage problems, assessed the adequacy of the O-ring seal between the glass tubes and the manifold.

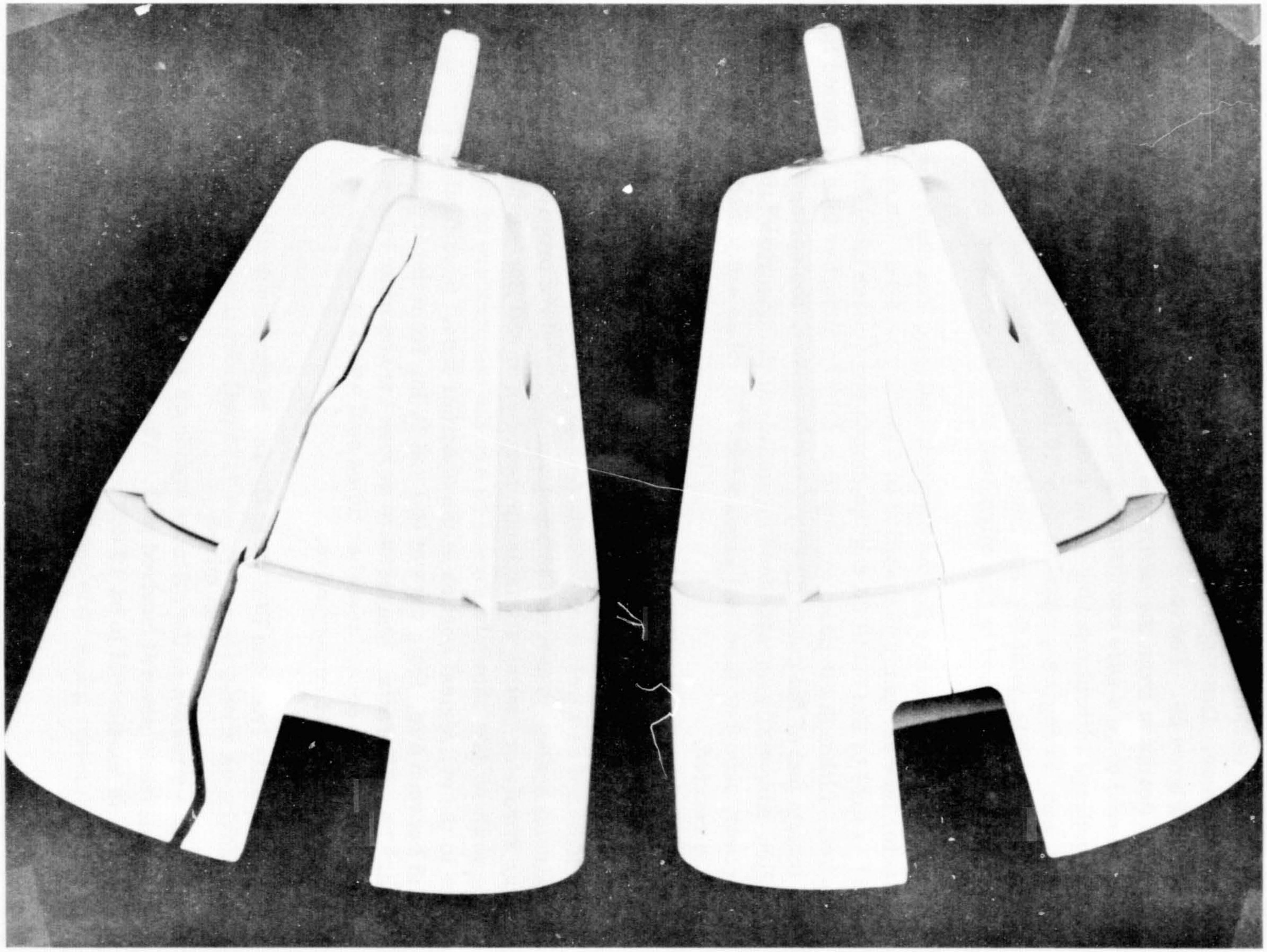

Figure 27. Tube support cup insert failure.

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The alignment study objective was to show that the tubes could not experience metal-to-glass contact in a binding condition as a normal situation. In all cases, worse-case tolerances were taken to ensure complete confidence in the outcome. Drawings of the tube, cup, and insulation were completed as shown in Figure 28. The normal maximum tolerance at the construction site is ±1/4 in. deviation from the horizontal, which is equivalent to 0.32 degree. This proved to be a safe condition. The maximum deviation which the tubes could undergo without touching some member other than the O-ring or flat gasket was ±4 degrees, equal to over 10 times the maximum on the installation drawings. At this point the tube could touch the outer edge of the insulation. The conclusion reached is that alignment tolerances cannot cause glass breakage.

As a prerequisite for the strength analysis, one must recognize that the collector tube assembly is installed in a manner whereby the open end (absorber tube) is held by the manifold and the closed end (cover tube) is held by a metal bracket. Although the dome or closed end of the absorber tube is seated inside the bottom end of the cover tube by a metal spring, the spring is flexible enough to allow essentially unrestrained movement of the absorber tube. Therefore, the cover/absorber tube seal area, where the tubes are joined, is where the load is reacted.

A strength analysis of this tube assembly was attempted using the BOSOR (Buckling of Shells of Revolution) Finite Element Model. The tube assembly was analyzed as a pressure vessel, and the parameters employed were the maximum system pressure (45 psia) and temperature profile derived from the solar simulator testing at maximum heat flux of 350 Btu/hr-ft^2. The reduced temperature data shown in Figure 29 are the temperature of the nonboiling interface in the cylindrical portion of the absorber tube. Specifically, the data were valid between 6 in. from the wet end and 12 in. from the dry end of the absorber tube. The differential temperature across the absorber tube wall was essentially zero. Also, the cover/absorber tubes seal was assumed to be rigidly fixed, which is somewhat conservative.

Results from the BOSOR analysis are shown with the model in Figure 30. The maximum stress ($S_{\text{von mises}}$ = 7410 psi) occurred at the seal while the membrane stresses in the cylinder and dome of the absorber tube were small (approximately several hundred psi). The ultimate strength of the KG33 glass material is considered to be 10 000 psi which is based on ASTM testing of 3/8-in. diameter glass rods and therefore somewhat questionable due to the

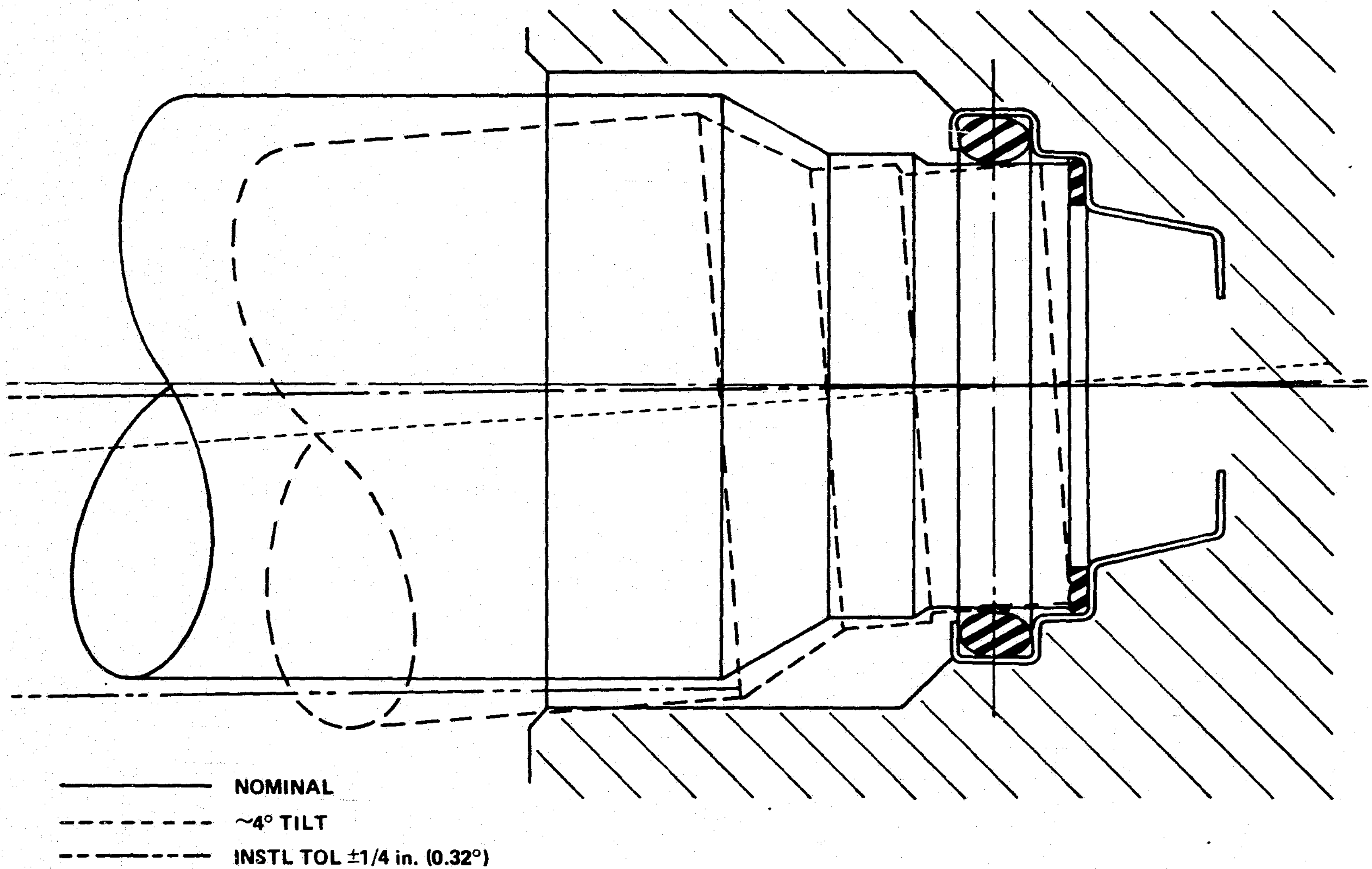

Figure 28. Alignment assessment.

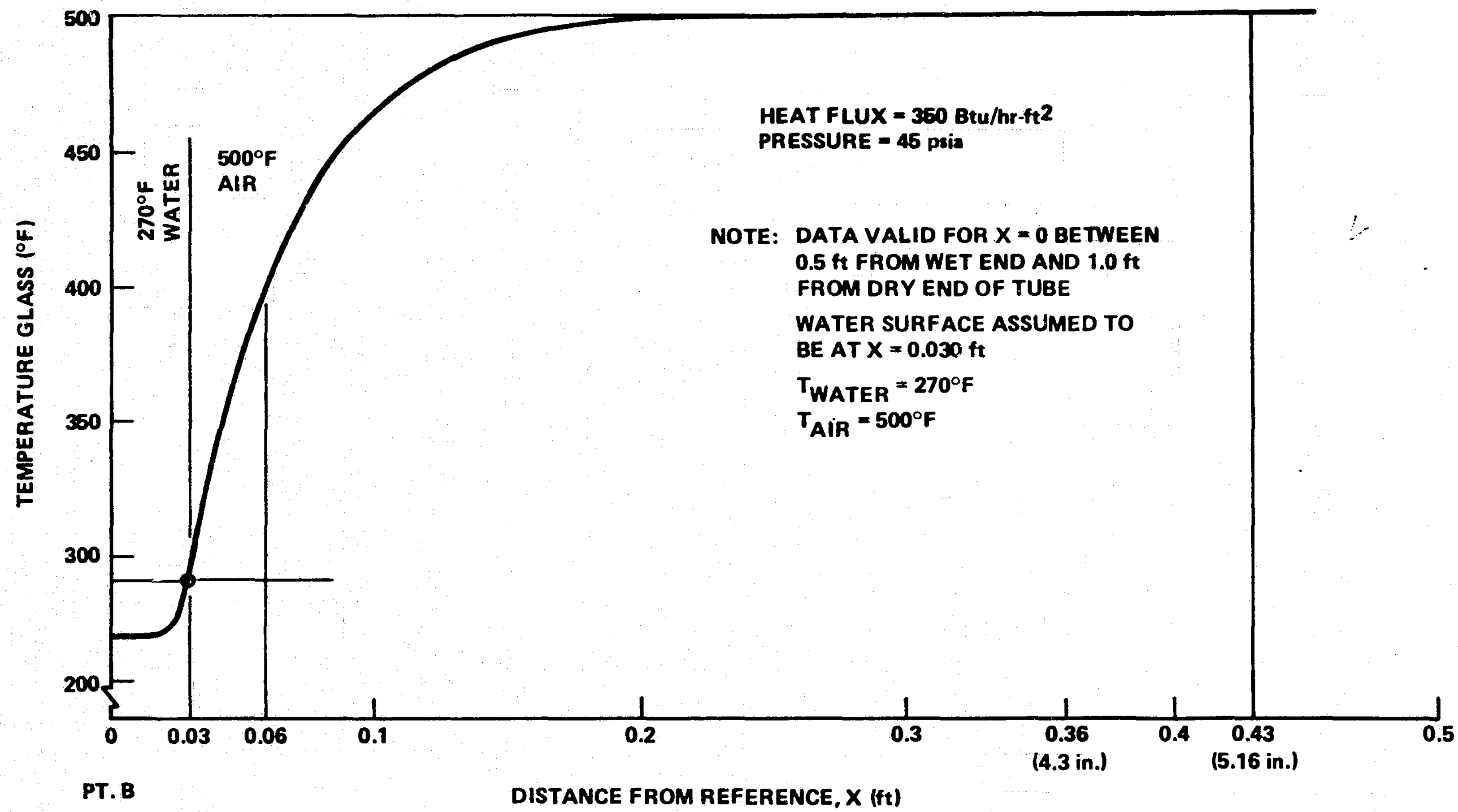

Figure 29. Temperature along absorber tube wall with nonboiling water/air interface.

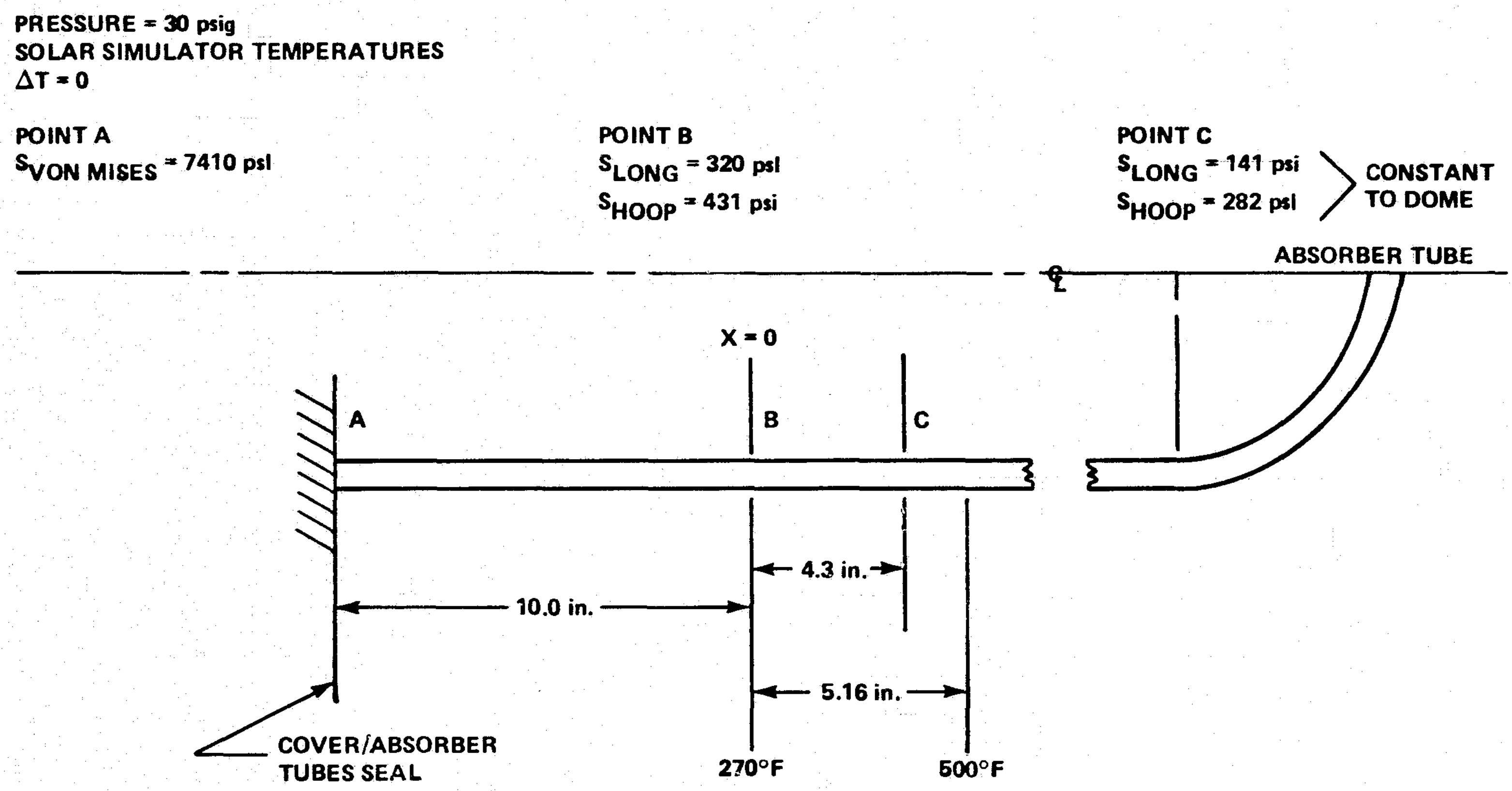

Figure 30. BOSOR — Finite Element Model of absorber tube.

difference in configuration. This value may be a little too high. Although this stress at the seal is considered conservative, there are still other unknowns in this area that should be determined to establish a valid margin of safety. These unknowns are residual stresses incurred during forming operations, more definitive temperature data in the seal area, and worse-case seal geometry.

Should it become necessary later to remove any assumption on end condition at the seal, an alternate APSA (Axisymmetric Planar Stress Analysis) Finite Element Model can be used. This program has elastic/plastic capability and can provide a refined grid mesh at the thicknesses of the various components as shown in Figure 31. Also, given sufficient time, tube assemblies strain gauged on the inside surface of the absorber tube could be added to the collector test article and tested in the solar simulator to verify the analytical results. One such tube assembly has been successfully strain gauged by the MSFC Electronics and Control Laboratory. This task was once thought to be too difficult or near impossible to accomplish when curved surfaces are involved.

Summarizing the strength analysis, it appears that the SUNPAK^{TM} tube assembly is structurally adequate; however, the required margin of safety cannot be ascertained at this time without accomplishing the previously mentioned tasks. Also, defects such as scratches, pits, etc., cannot be tolerated, particularly in the absorber tube. It was proven in hydrostatic testing [2] that the tube assemblies were weakened appreciably due to scratches on the absorber tube. Visual examination of tubes that were subjected to hydrostatic testing confirmed the occurrence of flaw propagation. Due to the absence of fracture toughness data, flaw growth with respect to the intended service life of the tube assemblies cannot be assessed. Therefore, it is considered mandatory that the tubes be screened during manufacturing and hydrostatically tested to 350 psig to eliminate those containing defects.

In studying the design of the O-ring and manifold cup as a possible source of leaks, the major criterion is the efficiency of the seal. In this case, drawings were completed using worse-case tolerances. Seal design appears to be adequate from the standpoint of compression of the O-ring with a 16-percent compression. This is within the limits set by the O-ring manufacturers. A proper pressure actuated seal is shown in Figure 32. Referring to Figure 28, the cup O-ring groove appears to be somewhat lacking in two areas. The inside taper does not have the manufacturers recommended 5-degree taper, and the outside lip of the cup is not as long as recommended, giving slightly less sealing area for the O-ring. These deficiencies are not considered significant to require a

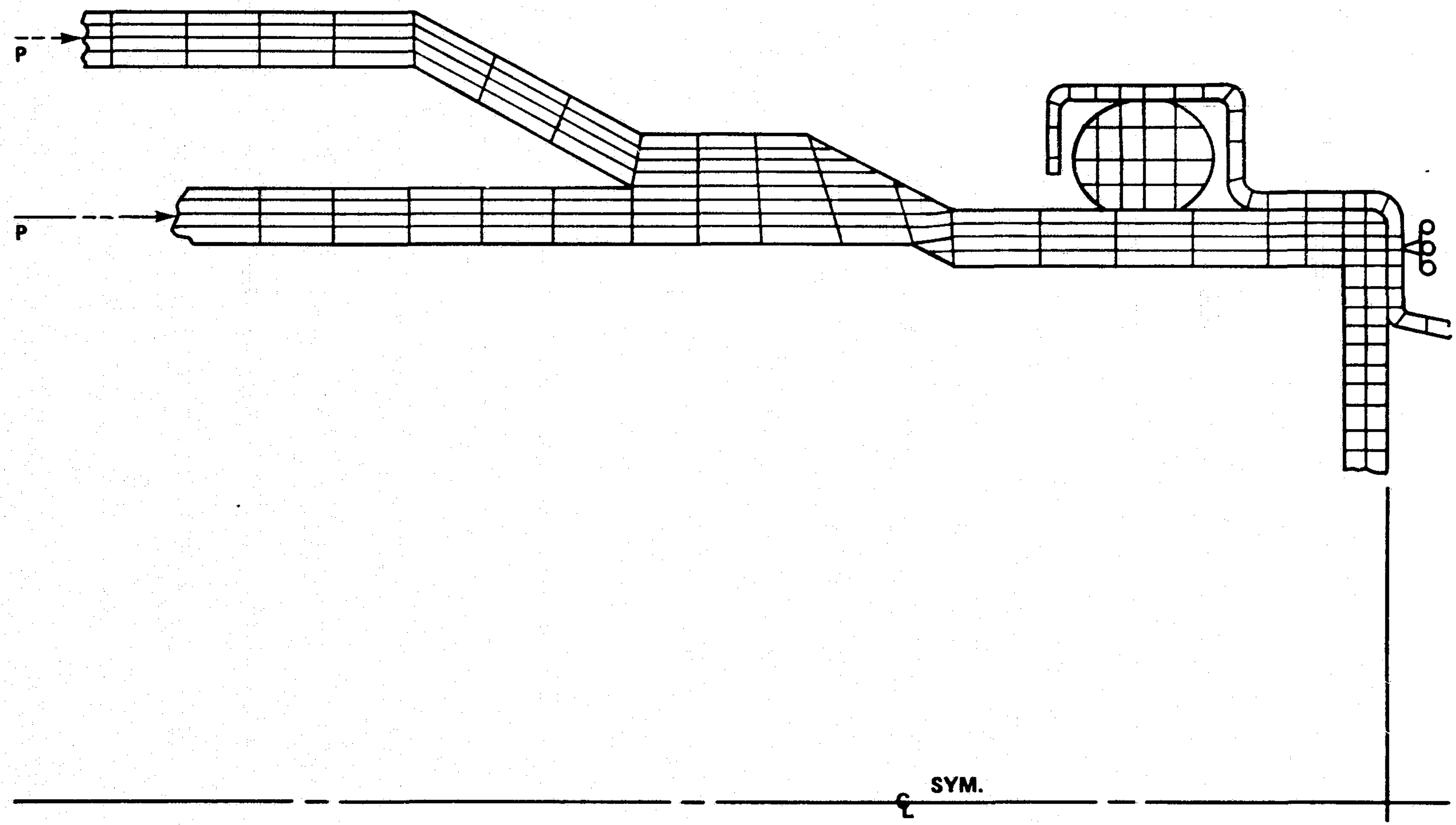

Figure 31. APSA Finite Element Model.

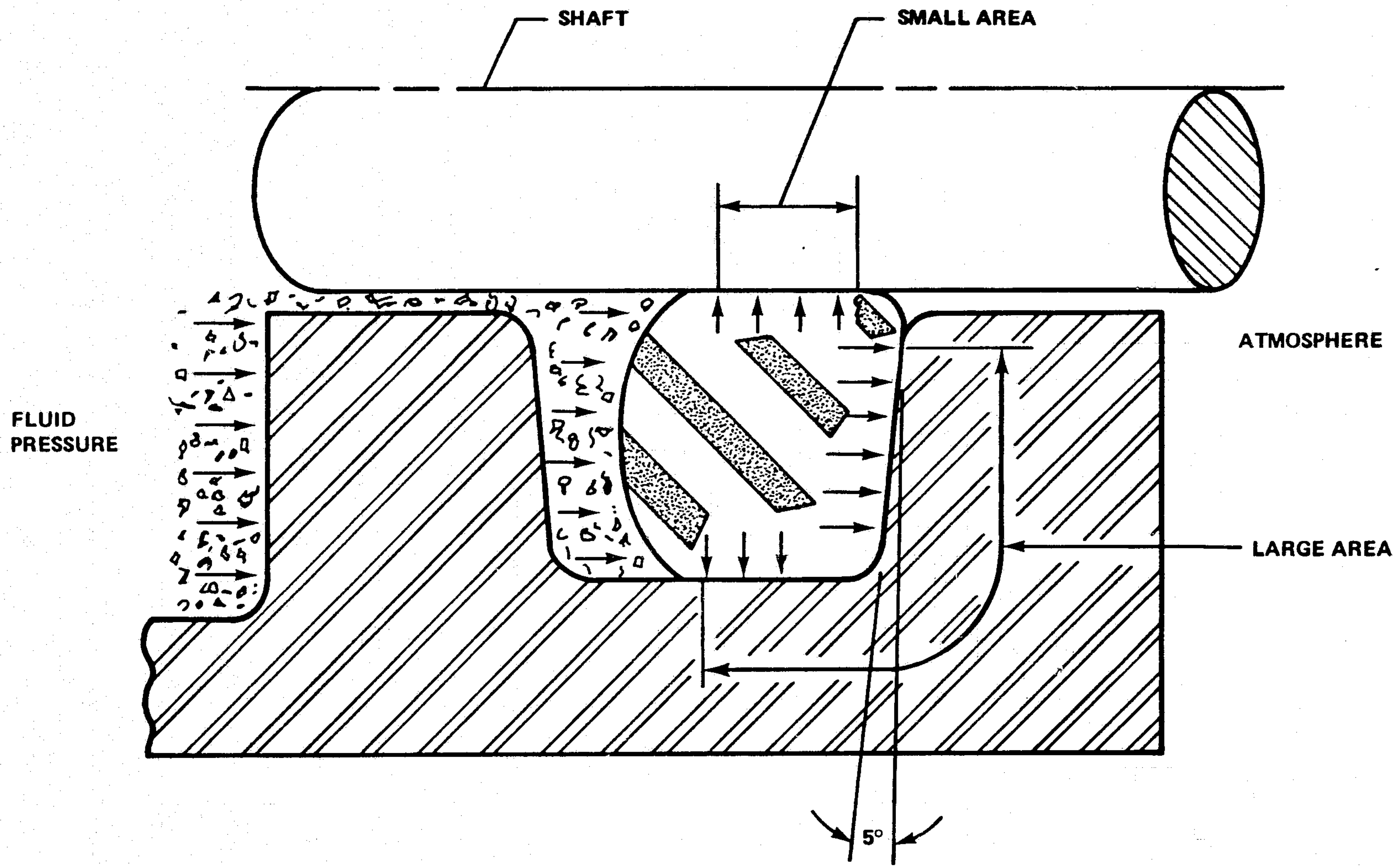

Figure 32. Pressure actuated seal.

redesign, especially since O-I has evolved this design over a period of time through testing and, according to available documentation, little trouble is experienced in this area. The MSFC Design Group believes that substantial sealing is also achieved from the flat gasket, which is not the intent. The gasket is actually intended to protect the edge of the open end of the absorber tube against the metal cup.

VI. MATERIALS EVALUATION [2]

A separate detailed report has been published by MSFC Materials and Processes Laboratory [2] to document the evaluation of materials used in the SUNPAK^{TM} collector. The five areas of investigation summarized here are glass components, coating stability, manifold components, plastic components, and rubber components.

Based on results obtained from hydrostatic testing of numerous collector tubes and the subsequent solar simulator testing, the SUNPAK^{TM} tubes (properly proof tested before installation) appear acceptable for operation including stagnation and boilout modes. These tests, however, were conducted for short periods of time; therefore, long-term service life or service performance with continued stagnation/boilout cannot be predicted. This can only be established by field experience, lengthy testing, and/or fracture mechanics studies. As with any glass manufacturing, the processes utilized should minimize the damage to the absorber tube. Final processing should include a proof test for applications of this type. 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.

The maximum temperature observed during testing in the solar simulator was 675°F (357°C) on the absorber tube. The simulated solar intensity was a worse-case condition. No change in the absorber coating was detected. Also, review of test results reported by O-I shows that rapid decrease in absorption efficiency of the coating will not occur until the coating is subjected to temperatures greater than 700°F (371°C). In these tests, collector tubes were held at elevated temperatures for an extended period of time, then allowed to heat in the Sun to acceptable stagnation temperatures. The temperature achieved during stagnation is a measure of the coating absorption efficiency. Other O-I data show that the design also assures a stable vacuum between the absorber tube and outer cover so initial performance should be maintained over long periods of time.

The process of joining the copper manifold elements with solder is not adequate; analysis and test show some joint areas are too small for carrying loads and the melting point of solder is too low for the temperatures of stagnation and boilout. Alternate solutions include a precision cast manifold with no soldered joints or a new design which would permit brazing the elements together. No significant degradation of the foam core of the manifold resulted during solar simulator tests; however, proper formulation and mixing of the foam are critical to ensure that the foam will not degrade. Higher temperature foams are identified should foaming with the current material become a problem. O-I will change the insulation cover to a fiberglass reinforced polyester composite material since the current gelcoat cover material tends to deform with heat.

The only plastic component identified as a potential problem area is the tube support cup insert shown in Figure 27. Higher temperature materials are identified to overcome the thermal softening which caused leaks experienced during the boilout tests. Also, the contact surface should be increased to a conical shape to improve distribution of the load transferred to it from the dome end of the collector tube.

The rubber material used for O-rings and end bumper seals withstood maximum temperatures observed during solar simulator tests. A higher temperature material is identified if product improvement is desired. The material used for feeder tube couplers and tip protectors is not suited for the observed temperature environment because it becomes "putty-like" during boilout and stagnation operation. The coupling is recommended to be designed into the grommet sealing the feeder tube at the center of the manifold where temperatures are lower. This would also allow a single standard feeder tube length. High temperature materials are identified for the tip protector application including a carbon material favored by O-I.

VII. QUALITY ASSURANCE EVALUATION [8]

Assessment of the quality assurance activities entailed a review of the manufacturing operations since no dedicated quality assurance organization was identified. At the time of this assessment, manufacturing was geared to limited production of development collectors in the O-I plant at Toledo, Ohio.

Control over glass quality was handicapped by the need for glass to be supplied by another O-I division where major production was providing glass for laboratory vessels for chemical and medical research. Receiving inspection of glass at the Toledo plant was done on a sampling basis only. Records showed that 50 to 80 percent of the incoming tube stock was being rejected for one or more deficiencies. This high rejection rate was cause for concern relative to the fitness of the supplied materials based on the sampling plan reviewed. A 100 percent inspection would preclude any defective glass used in the production of collector tubes. Even with the sample type inspection, O-I records showed adequate traceability for each component used in assembled tubes. This was possible from manufacturing logs kept at each step of processing.

All tubes produced for MSFC solar simulator testing were fully inspected, coded, and hydrostatically tested to 350 psig at O-I. Approximately 10 percent of these tubes failed the test. The remaining tubes were again subjected to hydrostatic test at MSFC to screen out any possible damage during shipping. The MSFC test followed ASME C601-70 proof pressure procedure. This requires slowly increasing the pressure at a rate of 100 psi/min, holding at 350 psig for 1.5 min, then slowly reducing the pressure to zero. Approximately 30 percent of the delivered tubes failed the test at MSFC. The difference between O-I and MSFC hydrostatic testing is that O-I increased pressure at a fast rate and did not hold pressure at 350 psig before rapidly reducing the pressure to zero. No tubes which survived the MSFC test were broken in subsequent boilout tests with the solar simulator. Nevertheless, O-I continued to use the rapid hydrostatic test for economic reasons and field experience with retrofitted systems since the MSFC test program supports this decision.

A study of the boxes used in shipping tubes from O-I to a user was made after several shipments to MSFC arrived damaged. The shock absorbing spacers in the box ends were judged too thin for protection. Also, the pallets used for handling several full packages of cardboard boxes were not large enough to preclude forklift handling damage. Redesign of the boxes and pallets was recommended to ensure more protection in shipping operations.

VIII. RECOMMENDATIONS

Subsequent paragraphs state the recommendations presented to ERDA in March 1977. The degree of acceptance and implementation of these recommendations by O-I can best be decided by subsequent users of the SUNPAK^{TM} collector.

Since no glass failures occurred during boilout tests when good tubes were used, a prime recommendation was to continue use of the SUNPAK^{TM} collector in ERDA demonstration projects. Near-term use, however, should require proof test of all tubes to 350 psig. Also, system designers and O-I user's manuals should recognize marginal materials identified by MSFC testing and adhere to the following system constraints:

a) No hot filling

b) Design and install systems to avoid hot-fills, boilout and stagnation conditions, and to provide freeze protection where required

c) Leak test assembled arrays at 55 psig or two times relief valve setting, if higher.

To maintain the baseline established during the MSFC assessment, it was recommended that O-I continue a rigorous program of configuration control over the design. Of special importance to this activity is thorough analysis and documentation of test results before future changes to the design baseline are approved.

A more formal quality assurance program was recommended for O-I to ensure that integrity of future delivered hardware will remain at the same level as the hardware used in MSFC testing. This program should be a cost effective balance between automated process controls and manual inspection activities.

A long-term recommendation was for O-I to provide stronger applications engineering support for SUNPAK^{TM} users. This would include additional reduction and evaluation of test data provided from MSFC solar simulator boilout tests to further understand the collector performance and constraints limits. A key tool to be located at O-I would be an array/ system breadboard to assess/ define collector interfaces in other operating modes and system configurations to help define positive collector drain schemes and reduce the number of applications constraints. End products from these activities will be more detailed applications guidelines and installation/ operations/ maintenance manuals.

A final recommendation was for ERDA to define the applicability of the NBS Interim Performance Criteria document for systems using the SUNPAK™ collector. O-I has identified additional costly testing to be accomplished if rigorous adherence to the Interim Performance Criteria becomes necessary.

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4. System Assessment of the Owens-Illinois Collector. Memorandum EL51(202-77), October 6, 1977.

5. Owens-Illinois (O-I) Collector Tests. Memorandum EP43 (77-50), July 14, 1977.

6. Use of the Marshall Space Flight Center Solar Simulator in Collector Performance Evaluation. DOE/NASA TM-78165, April 1978.

7. Owens-Illinois Solar Collector. Memorandum EP46(77-56), August 9, 1977.

8. Quality Assurance Assessment of Owens-Illinois SUNPAK. J. A. Waldrop note dated May 13, 1977.