AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

RFP-4874

RECEIVED
100 25 100
OSTI

A Study of the Utility of Heat
Collectors in Reducing the Response Time
of Automatic Fire Sprinklers Located
in Production Modules of Building 707

James H. Shanley, Jr.
Edward K. Budnick, Jr., P.E.

Hughes Associates, Inc.
2730 University Boulevard, West
Suite 902
Wheaton, Maryland 20902

Prepared For:

E G & G
Rocky Flats Plant
Golden, Colorado

January 1990

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

④
"REVIEWED FOR CLASSIFICATION
By L. C. Wing
Date 2-20-90"

Hughes Associates, Inc.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Contents

	<u>Page</u>
1.0 BACKGROUND	1
1.1 Problem Description	1
1.2 Scope and Objectives	1
2.0 APPROACH	3
3.0 LITERATURE REVIEW	4
3.1 Sprinkler System Design	4
3.2 Heat Collectors	4
3.3 Sprinkler Behavior and Response	6
3.4 Fire Plume Temperature and Velocity	6
3.5 Ceiling Jet Temperature and Velocity	9
3.6 Sprinkler Response Time Prediction	11
3.7 Sprinkler Suppression Capability	12
4.0 SITE SURVEY	13
4.1 Observations	15
4.1.1 Dimensions and Construction	15
4.1.2 Automatic Sprinkler System	15
4.1.3 Utilities and Obstructions	15
4.1.4 Fuel Loading	16
5.0 EXPERIMENTS AND TESTS	17
5.1 Small Scale Experiments	17
5.1.1 Apparatus and Procedure	17
5.1.2 Results	17
5.2 Full Scale Testing	20
5.2.1 Objective	20
5.2.2 Test Apparatus and Instrumentation	20
5.2.3 Test Procedure	20
5.2.4 Test Results	22
6.0 PROBLEM QUANTIFICATION/ANALYSIS AND RESULTS	26
6.1 Module Fire Hazard Assessment	26
6.2 Water Supply Evaluation - Extinguishment Limits	27
6.2.1 Baseline Sprinkler Design Water Density	27
6.2.2 System Capability	28
6.3 Sprinkler Response Time	29
6.3.1 The Concept of Sprinkler Response	29
6.3.2 Response Modeling	29
6.3.3 Baseline Response Modeling	29
6.3.3.1 Standard Response Sprinkler	30
6.3.3.2 Quick Response Sprinkler	33

Contents (Continued)

	<u>Page</u>
6.3.4 Sprinklers at Module Ceiling	
Response Modeling	33
6.3.4.1 Standard Response Sprinkler .	33
6.3.4.2 Quick Response Sprinkler . .	37
7.0 DISCUSSION AND EVALUATION OF ALTERNATIVES . . .	37
7.1 Heat Collectors	37
7.1.1 Performance Assessment	37
7.1.2 Conclusions "	39
7.2 Moving Existing Sprinklers	40
7.3 Changing Sprinkler Sensitivity	41
8.0 RECOMMENDATIONS	41
9.0 REFERENCES	42
APPENDIX A - Small Scale Collector Testing	A-1

Tables

<u>Table</u>	<u>Page</u>
1 Results of Required Delivered Density (RDD) for Extinguishment for Three Fuel Packages [9] . . .	13
2 Summary of Full Scale Test Runs	23
3 Test Results for 200 kW Heat Release Rate	24
4 Test Results for 500 kW Heat Release Rate	24
5 Test Results for 150 kW Heat Release Rate	25
6 Test Results for 1500 kW Heat Release Rate . . .	25
7 Test Results for t^2 Growing Fire	25
8 DETACT Baseline Sprinkler Response Time Predictions, Sprinkler Located at False Ceiling, 12 ft Above Fuel, $RTI = 250 \text{ (ft}\cdot\text{s)}^{1/2}$	31
9 DETACT Baseline Sprinkler Response Time Predictions, Sprinkler Located at False Ceiling, 12 ft Above Fuel, t^2 Growing Fire, $RTI = 250 \text{ (ft}\cdot\text{s)}^{1/2}$	31
10 DETACT Baseline Sprinkler Response Time Predictions, Sprinkler Located at False Ceiling, 12 ft Above Fuel, $RTI = 50 \text{ (ft}\cdot\text{s)}^{1/2}$	34
11 DETACT Baseline Sprinkler Response Time Predictions, Sprinkler Located at False Ceiling, 12 ft Above Fuel, t^2 Growing Fire, $RTI = 50 \text{ (ft}\cdot\text{s)}^{1/2}$	34
12 Result Summary of DETACT Modeling of Baseline System with Standard and Quick Response Sprinklers	34
13 DETACT Sprinkler Response Time Predictions, Sprinkler Located at Module Ceiling, 17.5 ft Above Fuel, $RTI = 250 \text{ (ft}\cdot\text{s)}^{1/2}$	35
14 DETACT Sprinkler Response Time Predictions, Sprinkler Located at Module Ceiling, 17.5 ft Above Fuel, t^2 Growing Fire, $RTI = 250 \text{ (ft}\cdot\text{s)}^{1/2}$.	35

Tables (Continued)

<u>Table</u>	<u>Page</u>
15 DETACT Sprinkler Response Time Predictions, Sprinkler Located at Module Ceiling, 17.5 ft Above Fuel, RTI = 50 (ft·s) ^{1/2}	36
16 DETACT Sprinkler Response Time Predictions, Sprinkler Located at Module Ceiling, 17.5 ft Above Fuel, t ² Growing Fire, RTI = 50 (ft·s) ^{1/2} .	36
17 Response Times for Standard Response (RTI = 249 (ft·s) ^{1/2}) Time Constant Discs from Full Scale Testing	38
18 Response Times for Standard Response (RTI = 47 (ft·s) ^{1/2}) Time Constant Discs from Full Scale Testing	38

Figures

<u>Figure</u>		<u>Page</u>
1a	Typical sprinkler system placed near ceiling . . .	2
1b	Sprinkler system without ceiling - fire located directly under sprinkler	2
1c	Sprinkler system without ceiling - fire located between sprinklers	2
2	Gaussian temperature and velocity profiles within a fire plume	8
3	Formation of a ceiling jet from impingement of a fire plume	10
4	Comparison of measured and t^2 growth rates	14
5	Small scale test heat collectors	18
6	Small scale test apparatus	19
7	Full scale test set up and instrumentation	21
8	t^2 fire growth rates	32

1.0 BACKGROUND

1.1 Problem Description

Several of the ten production Modules in Building 707 at the Department of Energy Rocky Flats Plant recently underwent an alteration which can adversely affect the performance of the installed automatic fire sprinkler systems. The Modules have an approximate floor to ceiling height of 17.5 ft. The alterations involved removing the drop ceilings in the Modules which had been at a height of 12 ft above the floor. The sprinkler systems were originally installed with the sprinkler heads located below the drop ceiling in accordance with the nationally recognized NFPA 13, Standard for the Installation of Automatic Sprinkler Systems [1]. The ceiling removal affects the sprinkler's response time and also violates NFPA 13.

The response time of the sprinklers, a critical performance parameter, may be increased significantly by the removal of the drop ceiling. In some cases, depending on the orientation and the growth characteristics of the fire, the system may fail to operate altogether. As shown in Figure 1a, the ceiling surface located just above the sprinklers re-directs the heat from a fire creating a ceiling jet. Under typical fire conditions one or more sprinkler heads will respond to this flow of hot gases across a ceiling. In the case of a sprinkler located directly above a fire, as shown in Figure 1b, in the absence of the ceiling, the heat which travels upward would probably only activate that sprinkler alone. If the fire is located between sprinklers, as shown in Figure 1c, then, without a ceiling the heat will rise past all of the sprinklers and in fact may not heat any of them. For this reason, sprinklers are typically installed near a ceiling surface. NFPA 13, section 4-3.1, requires that the sprinklers be no more than 12 in. below noncombustible ceilings. With the removal of the false ceilings the sprinklers will be located approximately 5.5 ft below the ceiling, a violation of the sprinkler standard.

1.2 Scope and Objectives

The scope of this study included evaluation of the feasibility of utilizing heat collectors to reduce the delays in sprinkler response created by the removal of the drop ceilings. The study also includes evaluation of substituting quick response sprinklers for the standard sprinklers currently in place, in combination with a heat collector.

Figure 1a Typical sprinkler system placed near ceiling

Figure 1b Sprinkler system without ceiling -
fire located directly under sprinkler

Figure 1c Sprinkler system without ceiling -
fire located between sprinklers

Specific objectives included:

1. Determine that the heat collectors are able to direct a sufficient quantity of the fire plume energy past a sprinkler to cause activation;
2. Determine the response time and minimum heat release rate for response of the existing sprinkler system, both before and after the removal of the false ceiling;
3. Determine the minimum size and geometry of the collector which gives an acceptable, minimum sprinkler response time; and,
4. Recommend a solution to the existing automatic sprinkler protection problem utilizing the results of this heat collector study.

2.0 APPROACH

The approach consisted of four areas of effort: literature review, building survey, testing and evaluation, and analysis. The literature review was used to gather as much information about heat collectors and associated areas as possible. This included fire plumes, sprinkler response modeling, sprinkler design requirements, and sprinkler suppression capability. Section 3.0 provides a summary of the findings of the literature search.

A survey of the affected Modules in Building 707 at Rocky Flats was conducted early in the project. This survey concentrated on determining the fuel loading and fire hazard of these Modules, documenting their basic geometries, and examining the existing sprinkler system designs.

Since the literature review indicated that little data was available on heat collector applications, tests were conducted to obtain more data on the performance of heat collectors. Both small and full scale tests were conducted to determine the optimum collector geometry, and size, and to evaluate the performance of a prototype collector.

Once the testing was completed, an analysis of the data was performed. The analysis included modeling the response of the sprinkler system both with the suspended ceiling in place and with the sprinklers relocated to the Module ceiling (e.g., 17.5 ft). Also included was an evaluation of the suppression capability of the sprinkler systems in the Modules.

Based on the test results and subsequent analysis, several conclusions and recommendations are provided regarding the use of heat collectors to solve the problem of no ceiling above the sprinklers.

3.0 LITERATURE REVIEW

3.1 Sprinkler System Design

Conventional automatic sprinkler design places the sprinklers near the ceiling of the compartment being protected for a number of reasons. Aside from just being out of harms way, being near a ceiling helps a sprinkler to activate in sufficient time to extinguish or control a fire. The ceiling acts to direct the energy rising above a fire towards the sprinklers located nearest the fire. Without a ceiling, most of the energy will rise past the level of the sprinklers and may only activate the single nearest sprinkler. The National Fire Code which addresses the design of sprinkler systems is NFPA 13, Installation of Sprinkler Systems [1]. NFPA 13, section 4-3.1, requires that the sprinkler deflector be located 1 to 10 in. below combustible ceilings or 1 to 12 in. below noncombustible ceilings. The operating elements of sprinklers must also be located below the ceiling. These requirements, which are based on extensive testing and experience, are intended to ensure sprinkler activation as well as a fully developed water spray pattern.

3.2 Heat Collectors

Typically when the ceiling of a room is moved or removed the sprinklers must also be moved. The proposed alternative to this is to install a flat shield or heat collector on each existing sprinkler. Although such devices have been used, their application, is not well documented in the literature and only one brief report was found which documented testing done by Union Carbide. The research by DeMonbrun and McCormick [2] involved the testing of three different heat collectors: round with an angled (45°) edge, square with a square (90°) edge, and a flat round plate. The collectors had dimensions of 10 in. diameter, 12 in. square, and 9 in. diameter, respectively. A standard response sprinkler head was placed in the center of each collector. The collector and sprinkler were placed 3 ft above a 30 gal. trash can filled to a level of 7 in. above its bottom with kerosene. The kerosene was ignited and the time for the sprinkler to activate was recorded.

The researchers concluded that the round and square collectors with an edge gave the best results and had a

significant affect on the time of sprinkler activation when compared to the no collector case. However, although they performed 70 runs and found the results promising, it is doubtful that these collectors would function in the same way when used in an actual installation. A major reason for this is the short distance between the fuel surface and the sprinklers in the test set-up. This distance was not given in the report but it was stated that the collector was 3 ft above the lip of the trash can containing the fuel. Assuming that the trash can lip was 2 ft high, the sprinkler would be approximately 5 ft above the fuel. In addition, the kerosene burned with a flame height of at least 2 ft and produced very dark and sooty smoke, which suggests that radiant heating of the sprinkler was significant. However, the purpose of a collector in theory is to enhance convective heating at significant distances from a fire where radiative effects are small, and it is convective heating which is largely responsible for the activation of conventionally designed sprinkler systems [3]. Had the collector and sprinkler been placed 8 to 12 ft above the fuel surface, the activation times would have been significantly higher because of the reduction in radiant heating (radiation decreases with the square of the distance).

The distance from the center of the collector and the burning fuel was also not explicitly stated, but it appears to have been approximately 3.5 ft. Increasing this distance to that produced by typical sprinkler spacing would also increase the response time significantly. Due to these limitations, the results of these tests can not be extrapolated to the geometries of concern in this study.

A brief discussion of heat collector use for automatic sprinkler systems was recently published by Fleming [4]. He mentions that "heat collector plates" have been used on numerous occasions in an attempt to improve sprinkler response. It is his contention, however, that the collectors may do more harm than good in that they may create dead air spaces around the sprinkler. This can delay sprinkler response by impeding convective heating. He cites the work done by DeMonbrun and McCormick [2] as a possible origin for the acceptance of heat collectors, but stresses that the results of that study are limited, and are not readily applied to full scale conditions.

NFPA 13, section A-3-11.8 [1] recommends that shields be provided on sprinklers which are under open gratings. It states that shields over automatic sprinklers should not be less, in least dimension, than four times the distance between the shield and fusible element. An exception to this is when special sprinklers are used which incorporate a built-in shield and are listed for the particular

application. This section of NFPA 13 is provided for information only and is not a requirement. The basis for the sizing of the collector or shield in this case, is not known.

The final reference to heat collectors was found in the catalog of the Automatic Sprinkler Corporation (part no. 87-751). A 20 gauge (0.035 in.), 12 in. square collector with a 3 in. edge on one side which tapers down to 3/4 in. is illustrated for use with sprinklers. They indicate that these collectors may be needed for outside exposure protection, suggesting that collectors may be intended more for the protection of the sprinkler from weather damage than for improving the activation time.

3.3 Sprinkler Behavior and Response

The heat activated device on an automatic fire sprinkler operates when the eutectic link material which holds the cap or valve mechanism together, softens from exposure to heat, the link comes apart, and the sprinkler opens. In the case of a glass bulb type sprinkler the eutectic link is replaced by a glass bulb filled with a liquid. When the liquid is heated, it expands causing the bulb to break and open the sprinkler.

There are three ways that heat is transferred to or from the sprinkler link. The majority of the energy transferred to the link from a fire is by convection. Additional heat may be transferred to the link by radiation, but this is usually small when compared to convective heating in typical fire situations. The link may lose heat by convection, radiation, and conduction. Conduction transfers heat from the link to other elements of the sprinkler. The rate of heat loss is usually significantly less than the heat gain. Heat loss by convection or radiation will occur only when the air around the sprinkler, or nearby objects, is less than the temperature of the link. Therefore, the sprinkler link (or other heat sensitive device) will be heated principally by a stream of heated air flowing past it, until it reaches its actuation temperature. This stream of heated air may be from the rising fire plume or from the jet which forms when the fire plume impinges on the ceiling and spreads radially outward.

3.4 Fire Plume Temperature and Velocity

The temperature and velocity of the gases surrounding and passing by a sprinkler head cause its response. The gases may be constituted in a fire plume, a ceiling jet, or a nearly quiescent environment. Several correlations were reviewed to determine the degree of applicability to the problem in this study.

Within a fire plume, the highest temperature will be found near the centerline of the plume and this temperature will decrease with height above the flame. Considerable work has been done on developing both theoretical and empirically based relationships for predicting plume centerline temperatures and velocity. A well recognized expression for centerline plume temperature is a correlation given by Heskestad [5]:

$$T_{CL} = T_a + 9.1 (T_a/gCp_a^2\rho_a^2)^{1/3} \dot{Q}_c^{2/3} (Z-Z_o)^{-5/3} \quad (1)$$

where:

T_{CL} = centerline plume temperature, K
 T_a = ambient temperature, K
 g = gravitational constant, m/s²
 Cp_a = ambient air heat capacity, J/kg K
 ρ_a = ambient air density, kg/m³
 $\dot{Q}_c$ = convective heat release rate, kW
 Z = height above fuel, m
 Z_o = virtual height
 $Z_o = -1.02 D + 0.083 \dot{Q}_c^{2/3}$
 D = fuel diameter, m
 $\dot{Q}$ = net heat release rate, kW

The centerline velocity, U_{CL} of the plume at a given height is estimated by another correlation given by Heskestad [5]:

$$U_{CL} = 3.4 (g/Cp_a T_a \rho_a)^{1/3} \dot{Q}_c^{1/3} (Z-Z_o)^{-1/3} \quad (2)$$

Moving away from the plume centerline, the temperature and velocity decrease. Assuming that the plume is symmetrical, the profiles of temperature and velocity are typically represented as Gaussian in shape, based primarily on empirical studies [5]. A Gaussian distribution, as shown in Figure 2, yields the following correlations for temperature and velocity at a point away from the centerline:

$$T_p = T_a + T_{CL} \exp(-(R/\sigma_T)^2) \quad (3)$$

$$U = U_{CL} \exp(-(R/\sigma_U)^2) \quad (4)$$

Figure 2 Gaussian temperature and velocity profiles within a fire plume

where:

R = radius, m
 σ_T = temperature plume width, m
 σ_U = velocity plume width, m

The quantities σ_T and σ_U are measures of the plume width, corresponding to the radii where local values of temperature rise and velocity are $e^{-1} = 0.368$, multiplied by the centerline values. For Gaussian profiles, the plume radii σ_T and σ_U are 1.201 multiplied by the plume radii b_T and b_U . The quantity b_T and b_U are the plume radii at the point where the temperature or velocity is 0.5 T_{CL} or 0.5 U_{CL} respectively.

The Gaussian profile has only been applied to the inner portion of the plume where the temperature and velocity are greater than or equal to one-half of their centerline value. Outside this limited radius, the correlation is considered weak, and there are no other reliable means of estimating the temperature or velocity. The turbulence and mixing caused by the entrainment of ambient air into the rising plume has made this a difficult task. This is a significant limitation relative to this study. The inability to predict the temperature and velocity conditions near the outer edge of a fire plume necessitated testing.

3.5 Ceiling Jet Temperature and Velocity

When the fire plume impinges on the ceiling the heat and buoyant gases are redirected, and flow radially outward from the impingement point in the form of a ceiling jet. This is shown in Figure 3. As the components of the jet flow outward under the ceiling, they entrain and mix with relatively cool air from below. With increasing radius, this leads to a continuous increase in thickness and decrease in the peak temperature and velocity of the ceiling jet. Immediately adjacent to the ceiling, the ceiling jet velocity is near zero and the temperature is approximately that of the ceiling. Below the ceiling surface, the temperature and velocity typically rise rapidly to its peak value and then, with increasing distance from the ceiling, the temperature and velocity continuously decrease. Further below the ceiling and near the edge of the ceiling jet, its temperature approaches the temperature of the lower ambient environment, and the velocity approaches zero.

Considerable work has been done on flow fields under ceilings, and a number of correlations have been developed to predict the temperature and velocity of a ceiling jet. One of the earliest was by Alpert [6]:

Figure 3 Formation of a ceiling jet from impingement of a fire plume

$$T_{cj} = T_a + 16.9 \dot{Q}^{2/3}/H^{5/3} \quad \text{for } r/H \leq 0.18 \quad (5)$$

or,

$$T_{cj} = T_a + 5.38 (\dot{Q}/r)^{2/3}/H \quad \text{for } r/H > 0.18 \quad (6)$$

$$U_{cj} = 0.96 (\dot{Q}/H)^{1/3} \quad \text{for } r/H \leq 0.15 \quad (7)$$

or,

$$U_{cj} = 0.195 \dot{Q}^{1/3} H^{1/2} r^{-5/6} \quad \text{for } r/H > 0.15 \quad (8)$$

where:

T_{cj} = ceiling jet temperature, K
 T_a = ambient temperature, K
 $\dot{Q}$ = heat release rate, kW
 H = ceiling height above fuel, m
 r = radius from plume centerline, m
 U_{cj} = ceiling jet velocity, m/s

Further work by Heskestad and Delichatsios [7] refined the temperature correlation to:

$$T_{cj} = T_a + 2.75 (0.188 + 0.313 r/H)^{-4/3} \dot{Q}^{2/3}/H^{5/3} \quad \text{for } r/H < 8.0 \quad (9)$$

3.6 Sprinkler Response Time Prediction

These correlations in combination with a sprinkler response equation can be used to predict sprinkler response for a given fire size and spacing. The applicable sprinkler response time equation is:

$$t_r = RTI U^{-1/2} \ln((T_g - T_a)/(T_g - T_r)) \quad (10)$$

where:

t_r = response time, s
 RTI = response time index, $(m \cdot s)^{1/2}$
 $RTI = m C_p U^{1/2} / h A$
 m = mass of sprinkler element, kg
 C_p = heat capacity of sprinkler element, J/kg K
 U = air flow velocity past sprinkler element, m/s
 h = convective heat transfer coefficient, J/m²sK
 A = surface area of sprinkler element, m²
 T_g = temperature of gas stream, K
 T_r = sprinkler activation temperature, K

These correlations and equations have been incorporated into a computer model written by Evans at the Center for Fire Research at the National Institute of Standards and Technology (CFR-NIST) which is called DETACT [8]. DETACT was utilized in this analysis to predict sprinkler response times for the Modules in Building 707 both before the alteration, with the false ceiling in place, and assuming the sprinklers had been moved up to the ceiling.

3.7 Sprinkler Suppression Capability

Research has recently been conducted by the National Fire Protection Research Foundation (NFPRF) to quantify the required delivered density (RDD) of several fuel packages [9]. The RDD is a measure of the critical water flux or density (gpm/ft²) to achieve extinguishment of a particular fuel type and configuration and at a specific burning rate. This testing was part of a larger effort to develop a design procedure for quick response sprinklers.

This research involved full scale tests where fuel packages were burned and water was applied at a specific density. For each of three fuel packages, the water density was started at 0.025 gpm/ft² and increased in subsequent tests until extinguishment was achieved. The three fuel packages tested were upholstered furniture, a plastic commodity stacked in cardboard boxes to a height of 6 ft, and wood cribs. Table 1 shows the results from the test runs where extinguishment was achieved. The upholstered furniture and wood cribs required a water density which was much less than the plastic commodity. This was attributed to the high degree of shielding present in the stacked and boxed plastic commodity which impeded water penetration to the seat of the fire.

Although the results of these tests are limited in scope, they provide valuable information on the suppression capability of sprinklers. The growth rate of the upholstered furniture and plastic commodity fuels can be approximated by an ultrafast t^2 growth rate as shown in Figure 4. The 120-150 second offset from the ultrafast curve is due to the ignition time of the fuel. RDD needed to extinguish a fire with these peak heat release rates and an ultrafast growth rate is applicable to other similar fuels where the shielding of the water spray is not severe.

Table 1. Required Delivered Density (RDD) for
Extinguishment for Three Fuel Packages [9]

Upholstered Furniture

<u>Total HRR*, kW</u>	<u>RDD, gpm/ft²</u>
150	0.05
1000	0.08
1500	0.10
2000	0.12

Plastic Commodity

<u>Total HRR, kW</u>	<u>RDD, gpm/ft²</u>
400	0.35
515	0.45

Wood Cribs

<u>Total HRR, kW</u>	<u>RDD, gpm/ft²</u>
215	0.06
250	0.10

*HRR - heat release rate

4.0 SITE SURVEY

A survey was conducted of the affected Modules in Rocky Flats Building 707. Information documented through the survey included physical dimensions, fuel loading, and construction. Specific data pertaining to the sprinkler systems included spacing, sprinkler type, and water supply.

The survey was performed on July 11, 1989 by two fire protection engineers from Hughes Associates, Inc. The areas surveyed were Module K, A, and C. The remaining Modules were not accessible for security reasons, but it was stated by the site fire protection engineer, Bruce Campbell, that the accessible areas were typical and he did not feel that there were any significant differences between the surveyed and unaccessible areas.

Figure 4 Comparison of measured and i^2 growth rates

4.1 Observations

4.1.1 Dimensions and Construction

The Modules form an interconnected production area. The Modules are separated by gypsum wall construction with a fire resistance rating of approximately 1 hour. The ceiling was poured, monolithic, 2 way joist type with steel reinforcement. The joists had dimensions of approximately 18 in. by 6 in. thick with a separation of 4 ft. The floor to ceiling height was approximately 17.5 ft. The drop ceiling, which in some cases had been completely removed and in other cases only partially removed, was approximately 12 ft above the floor. The Modules did not all have the same floor area. Module K was approximately 96 ft by 27 ft. Modules A and C were approximately 140 ft by 50 ft.

4.1.2 Automatic Sprinkler System

The sprinkler system had a spacing of approximately 12 ft between sprinklers and 10 ft between branch lines. The sprinklers themselves were located at the level of the drop ceiling, 12 ft above the floor. The sprinkler system branch lines were located approximately 2.5 to 3 ft above the drop ceiling. The sprinklers were rated at 165°F and were the Duraspeed model manufactured by Grinnel Corporation. Design drawings of the sprinkler system in the Modules were provided by Rockwell International. The drawings indicate that the systems were designed by Viking National Fire Sprinkler Corporation of Kansas City, Kansas in September of 1968. The plans indicate the pipe diameters, fittings and lengths. The data was used for the hydraulic analysis discussed in Section 6.2.1.

4.1.3 Utilities and Obstructions

To provide the power and special containment ventilation required by the processes in these Modules, extensive electrical conduit, pipes, and ventilation ductwork existed. They were primarily concentrated above the 12 ft level, where the ceiling had been, but there were also places where they were lower. The quantity of these conduits and ducts varied from moderate to high. In some places, they occupied 60 to 80% of the upper room volume. In some cases, the ceiling could not be seen through the maze of pipes and ductwork.

In our judgement, it is unlikely that these obstructions would have significantly interfered with the activation of or discharge of water from the sprinkler system under the original installation conditions. But, if the sprinkler systems were moved to the ceiling, these obstructions would likely impair the ability of the sprinklers to activate and

deliver water to the base of a fire occurring in the lower portion of the room. This could change the fire risk associated with operations in these Modules considerably.

4.1.4 Fuel Loading

The combustible materials observed in the Modules included gloveboxes, plywood waste crates, polyethylene sheets, office type furniture, books and manuals, ordinary waste, and combustible liquids, such as cutting oils. In addition to these materials, an unknown amount of plutonium is likely to be present in the Modules while the production process is active. The plutonium would only be present in the gloveboxes.

A glovebox is a sealed box constructed of stainless steel, lead, plexiglass, and lead-impregnated, neoprene gloves. The gloveboxes are typically inerted with nitrogen so that the oxygen concentration remains below 5% and are provided with ventilation which maintains a negative pressure relative to the room. They allow for the manual manipulation and machining of plutonium. The gloveboxes are generally interconnected so that the plutonium can be worked on in an assembly line-like process. A fire rated door on a fusible link is provided to separate sections of the glovebox in case of fire. Heat detectors are provided in the gloveboxes as well. The size of the gloveboxes varied but were usually not any smaller than 6 ft by 4 ft by 4 ft high.

The other principle fuel packages observed in the Modules were plywood waste storage crates. These crates were constructed of 1/2 in. plywood and were approximately 7 ft by 4 ft by 4 ft high. They are used for the storage of low level radioactive waste. Only one of these crates was observed during the survey, and that was in Module K. The site fire protection engineer stated however, that it would not be uncommon to find one or more of these crates in other Modules.

Polyethylene sheets were hung as a tent in some areas, presenting a large surface area. However, when exposed to heat this thermoplastic material shrinks, melts and pulls away from the heat source. Once ignited, it tends to drip molten, burning plastic. Being very thin, there is little mass and the heat release rate is not very large relative to other typical polymers. The remainder of the observed combustible material was of limited quantity and did not represent a large fuel loading.

5.0 EXPERIMENTS AND TESTS

5.1 Small Scale Experiments

A series of small scale experiments were designed and carried out to determine the effect of the heat collector geometry on temperature and velocity conditions. The experiments involved evaluating round and square collectors, with and without an edge. In some cases the edge was at a 90° angle to the collector and in others it was approximately 45°.

5.1.1 Apparatus and Procedure

The round collector, as shown in Figure 5, had an 8 in. diameter and the square collector was 8 in. by 8 in. A brass time constant disc was placed in the center of the collectors. This disc had a thickness of 1/32 in. and a diameter of 3/8 in. Type K thermocouple wire was welded to the disc. This disc had been previously calibrated and was found to have an RTI* of 47 (ft·s)^{1/2}. The thermocouple wires were connected to a strip chart recorder.

Two collectors were positioned equal distances from the center of the plume produced by the heat source, as shown in Figure 6. The heat source consisted of a small laminar propane flame. Once the flame was ignited the strip chart recorded the millivolt output from the two time constant discs. The test was continued until a steady signal was received. A more detailed test report is provided in Appendix A.

5.1.2 Results

The results of the small scale experiments, documented in Appendix A, indicated that a flat collector caused the time constant discs to respond faster with the flat collector than the collectors which had an edge. It is possible that the edge hindered the response of the discs by trapping buoyant air and plume gases in the collector, which became stagnant. Without a steady flow of gases past the disc, the rate of convective heat transfer is reduced significantly.

* RTI (Response Time Index) is a measure of thermal response derived from measurements obtained by plunging a thermal device in a hot air stream.

Round Collector
with Edge

Square Collector
with Edge

Flat Collector

Figure 5 - Small scale test heat collectors

(Not to Scale)

Figure 6 Small scale test apparatus

In the case of a flat collector, a jet is created when all or part of the plume impinges on it and this jet is able to move under the collector and past the disc without being hindered by a lip. Between the round and square collectors, there was no discernable difference.

5.2 Full Scale Testing

5.2.1 Objective

To evaluate the performance of a flat collector in a full scale environment, a series of tests was run utilizing a 5 ft by 5 ft collector and a heat source capable of heat release rates in excess of 1500 kW. The objectives of these tests were to (1) determine if a heat collector would improve sprinkler response and (2) identify the minimum size of the collector.

5.2.2 Test Apparatus and Instrumentation

The test apparatus consisted of the collector suspended 12 ft above the fuel surface. As shown in Figure 7, 26 thermocouples, 4 time constant discs (3 quick response ($RTI = 47 \text{ (ft}\cdot\text{s)}^{1/2}$) 1 standard ($RTI = 249 \text{ (ft}\cdot\text{s)}^{1/2}$) and 2 bi-directional velocity probes were used to instrument the collector. The time constant discs were used to represent quick response or standard response sprinklers. In addition, for some of the test runs, standard or quick response sprinklers were placed in the center of the collector. The objective of the instrumentation placed under the collector was to determine the temperature at various places under the collector. The time constant discs were used to simulate sprinklers and to determine how fast they would react under the various test conditions.

The heat source consisted of a natural gas sand burner which was 1 sq. ft in area and was capable of producing heat release rates of 100 to 1500 kW. The flow rate of the natural gas to the burner was measured using a turbine flow meter. The burner was fed by flexible hose which allowed it to be moved as required in the test procedure. The two collectors were constructed of carbon steel or a special fire resistant fiberglass and both were flat, 5 ft by 5 ft and approximately 1/4 in. thick. The collector was suspended from the ceiling of a high bay steel building which was sealed as much as possible to prevent drafts.

5.2.3 Test Procedure

The test runs were conducted at various constant heat release rates shown in Table 2 as well as two growing fire

Figure 7 Full scale test set-up and instrumentation

scenarios. The growing fires followed a t^2 curve and corresponded to a slow and fast fire as described in NFPA 72E, Standard on Automatic Fire Detectors [10]. Also shown in Table 2 is the position of the burner for the test runs and the type of sprinkler used.

The burner was moved away from the center of the collector at regular distance intervals for each run. This was done to determine how well the collector worked when the heat source was moved from directly under it. This simulated the case of a burning fuel being located between sprinklers. The spacing of the sprinklers in the Building 707 Modules was approximately 10 ft by 12 ft. This gives a maximum horizontal distance between sprinklers of 15.6 ft, with 7.8 ft being the maximum horizontal distance from any single sprinkler. This maximum horizontal distance dictated that for the tests the maximum distance between the edge of the 5 ft by 5 ft collector and the centerline of the heat source be 5.3 ft.

Once the data acquisition system was running, the test fire was ignited. The gas flow rate had been set for the desired constant heat release rate prior to each test run. The test was continued until the time constant disc which simulated the response characteristics of a typical standard sprinkler ($RTI = 249 \text{ (ft}\cdot\text{s)}^{1/2}$) reached a temperature of 165°F or until 15 minutes had elapsed. Prior to beginning the next test the test apparatus was allowed to cool to ambient temperature, the sprinkler was replaced if necessary, and the burner was placed in a new position.

5.2.4 Test Results

The response time of the time constant discs located at the center of the collector, discs 1 and 2, and the single test sprinkler placed in the center of the collector are shown in Tables 3 through 7 for various heat release rates. The response time is defined here as the time for the disc to reach a temperature of 165°F, which is the activation temperature of the sprinklers in the Modules in Building 707. The response time of the test sprinkler is the time required for the sprinkler to activate. These tables show the results for the constant heat release rates of 150, 200, 500 and 1500 kW for both the fiberglass and steel collectors.

The response times increase as the heat source is moved away from the center of the collector and, the response times decrease with an increase in the heat release rate. In some cases the disc did not reach the activation temperature of 165°F. In these cases, it is obvious that the collector does not enhance the response of the sprinkler. The response times of the sprinklers when they were used, were in many

Table 2. Summary of Full Scale Test Runs

<u>Run Number</u>	<u>Collector</u>	<u>HRR (kW)</u>	<u>Burner Position</u>	<u>Test Sprinkler</u>
1	FG	200	CL	None
2	FG	200	0	None
3	FG	200	1	Std.
4	FG	200	2	None
5	FG	200	3	None
6	FG	150	2	None
7	FG	100	1	None
8	FG	500	3	None
9	FG	500	2	None
10	FG	500	0	None
11	FG	500	CL	None
12	FG	500	5.3	None
13	FG	1500	5.3	None
14	FG	1500	3	None
15	S	150	1	Std.
16	S	150	2	None
17	S	150	0	QR
18	S	200	1	Std.
19	S	200	0	None
20	S	200	2	QR
21	S	200	3	None
22	S	500	1	Std.
23	S	500	2	None
24	S	500	3	None
25	S	500	5.3	None
26	S	1500	3	QR
27	S	1500	5.3	QR
28	S	Slow	1	QR
29	S	Fast	1	QR
30	S	Velocity	1	None

Notes:

1. FG and S stand for fiberglass and steel plates, respectively.
2. CL stands for the centerline of the collector. Distance measurements are from the edge of the collector.
3. Std. and QR stand for standard and quick response sprinklers, respectively.
4. Run 30 was conducted at HRRs of 100, 200, 500, and 1500 kW to calibrate the velocity probes.

Table 3. Test Results for 200 kW Heat Release Rate

Run No.	Pos*	Col**	Response Time, s		Sprinkler#
			Disc 1	Disc 2	
2	0	F	15	66	NT
3	1	F	15.6	144	ST 44
4	2	F	300	468	NT
5	3	F	540	DNR***	NT
18	1	S	93	216	ST 197
19	0	S	30	126	NT
20	2	S	285	627	QR 285
21	3	S	570	DNR	NT

Disc 1: RTI = 47 (ft·s)^{1/2} Disc 2: RTI = 249 (ft·s)^{1/2}
 * Position indicates distance from edge of collector, ft.,
 CL indicates collector centerline
 ** Collector type: F = FX Fiberglass, S = Steel
 *** DNR = Did not respond
 # Sprinkler type: ST = standard, QR = quick response,
 NT = not tested

Table 4. Test Results for 500 kW Heat Release Rate

Run No.	Pos*	Col**	Response Time, s		Sprinkler#
			Disc 1	Disc 2	
8	3	F	222	666	NT
9	2	F	57	285	NT
10	0	F	12	48	NT
11	CL	F	15.3	55	NT
12	5.3	F	DNR***	DNR	NT
22	1	S	27	102	ST 56
23	2	S	87	141	NT
24	3	S	276	321	NT
25	5.3	S	DNR	DNR	NT

Disc 1: RTI = 47 (ft·s)^{1/2} Disc 2: RTI = 249 (ft·s)^{1/2}
 * Position indicates distance from edge of collector, ft.,
 CL indicates collector centerline
 ** Collector type: F = FX Fiberglass, S = Steel
 *** DNR = Did not respond
 # Sprinkler type: ST = standard, NT = not tested

Table 5. Test Results for 150 kW Heat Release Rate

Run No.	Pos*	Col**	Response Time, s		Sprinkler#
			Disc 1	Disc 2	
6	2	F	DNR	DNR	NT
15	1	S	114	444	ST 426
16	2	S	900	DNR	NT
17	0	S	42	216	QR 48

Disc 1: RTI = 47 (ft.s)^{1/2} Disc 2: RTI = 249 (ft.s)^{1/2}
 * Position indicates distance from edge of collector, ft,
 CL indicates collector centerline
 ** Collector type: F = FX Fiberglass, S = Steel
 *** DNR = Did not respond
 # Sprinkler type: ST = standard, NT = not tested

Table 6. Test Results for 1500 kW Heat Release Rate

Run No.	Pos*	Col**	Response Time, s		Sprinkler##
			Disc 1	Disc 2	
13#	5.3	F	DNR	DNR	NT
14	3	F	72	204	NT
26	3	S	84	180	QR 126
27	5.3	S	213	576	QR 336

Disc 1: RTI = 47 (ft.s)^{1/2} Disc 2: RTI = 249 (ft.s)^{1/2}
 * Position indicates distance from edge of collector, ft,
 CL indicates collector centerline
 ** Collector type: F = FX Fiberglass, S = Steel
 *** DNR = Did not respond
 # Test stopped after 120 s
 ## Sprinkler type: QR = quick response, NT = not tested

Table 7. Test Results for t² Growing Fire

Run No.	Pos*	Col**	Response Time, s		Sprinkler#
			Disc 1	Disc 2	
28-Slow	1	S	123	210	QR 144
29-Fast	1	S	52	144	QR 54

Disc 1: RTI = 47 (ft.s)^{1/2} Disc 2: RTI = 249 (ft.s)^{1/2}
 * Position indicates distance from edge of collector, ft,
 CL indicates collector centerline
 ** Collector type: F = FX Fiberglass, S = Steel
 *** DNR = Did not respond
 # Sprinkler type: QR = quick response

cases close to the time for the corresponding time constant disc to reach 165°F. This indicates that the data from the time constant discs was representative of sprinkler response.

6.0 PROBLEM QUANTIFICATION/ANALYSIS AND RESULTS

6.1 Module Fire Hazard Assessment

Typical fuels observed in the Modules in Building 707 included such items as gloveboxes, plywood crates, office type furniture, polyethylene sheets and refuse. These combustibles are classified as ordinary. Combustible liquids were also observed, but in very small quantities. Ignition of these liquids would most likely result in small, isolated, low energy release rate fires.

The quantity of plutonium, a combustible and pyrophoric metal, present in the gloveboxes at any given time is not known. However, a water sprinkler system would not provide adequate fire protection for a plutonium fire anyway due to the reaction between the plutonium and the water. We inferred from this that the role of the sprinkler system is to control/extinguish fires which spread beyond the ignition of the plutonium, or which originate in the other combustibles.

The primary fuel packages are the gloveboxes and the plywood crates. The fire threat and fuel loading posed by these fuels were discussed in depth in a report done by Hughes Associates, Inc. for Building 776/777 [13]. In that study, it was concluded that the plywood crate had a potential peak heat release rate of approximately 2100 kW and the growth rate was considered to be somewhere between the fast and ultrafast t^2 growth curves. The gloveboxes have combustibles in the form of neoprene, lead lined gloves, polycarbonate (lexan) or polymethyl methacrylate (plexiglass) view windows, and in some cases Benelex. Benelex is a high density, pressed wood fiberboard which was typically 3 inches thick on parts of the glovebox. The peak heat release rate of the glovebox was estimated to be 2700 kW. The growth rate of this package was more difficult to predict because of its multi-component composition. However, a conservative assumption of a fast growth rate was made for the analysis. Other combustibles considered in the previous report had peak heat release rates which ranged from 100 to 500 kW. From the results of the survey done of the Modules in Building 707 it is not considered likely that any of the fuel packages alone could have a peak heat release rate greater than 2700 kW.

It is anticipated that these fuels, once ignited, would sustain combustion and the heat release rate would increase

with time until the peak was reached. When fuel packages are located adjacent to each other, there is the possibility that multiple fuel packages could ignite and burn simultaneously. In this case, the heat release rate could be substantially greater.

If the sprinkler system does not operate prior to or soon after some critical heat release rate is reached, the sprinkler may be incapable of extinguishing the fire. When the fire cannot be extinguished by the closest sprinklers, it will continue to burn and its heat release rate will increase. This can cause additional sprinklers to open which will decrease the applied water flux (e.g., density) and may or may not extinguish the fire.

6.2 Water Supply Evaluation - Extinguishment Limits

6.2.1 Baseline Sprinkler Design Water Density

To evaluate the suppression capability of the existing sprinkler system, a hydraulic analysis was done using the Gessler Group Hydraulic Analysis Computer Program [11]. The input for this program consisted of the pipe diameters, pipe length and fittings from the most remote sprinkler in Module A of Building 707, to the base of the riser. Water supply data was obtained from the water supply study done by Hughes Associates, Inc. [12]. At Building 707, the water supply study indicated that the static pressure was 88 psi and that a residual pressure of 70 psi was obtained while flowing approximately 970 gpm. For the purpose of the analysis it was assumed that the sprinklers had a 1/2 in. orifice which is a standard orifice size with a flow coefficient of 5.6 gpm (psi)^{-1/2}.

The results of the analysis indicate that the pressure at the most remote sprinkler will be approximately 69.3 psi, which will result in sprinkler discharge of approximately 46.6 gpm. Applied over the sprinkler coverage area of 120 ft² this flow rate yields a water application density of 0.39 gpm/ft².

This density is greater than the Extra Hazard Group 2 density specified by NFPA 13. Section 2-2.3 and Figure 2-2.1.1(b) of NFPA 13 show that over an area of 2500 ft² the design density for Extra Hazard Group 2, the most severe fire hazard considered by NFPA 13, is required to be a minimum of 0.37 gpm/ft².

It is not likely that the sprinkler systems in these Modules were designed with the intent of delivering this much water. The excellent water supply at Building 707 combined with the fact that the hydraulic analysis was done with only

a single sprinkler open, resulted in the high estimate of the water density. A single head was considered because without the ceiling in place it would be difficult to open multiple sprinklers. When the hydraulic analysis is done for an area of sprinkler operation of 1500 ft² which includes 13 sprinklers, the water application density is reduced to 0.31 gpm/ft² at the most remote sprinkler. This water density falls between the density requirements of Extra Hazard Groups 1 and 2 in NFPA 13.

The volumetric rate of water applied to the surface area of a burning fuel needed to extinguish that fire has been referred to as the Required Delivered Density (RDD). As discussed in the Literature Search section of this report, Section 3.7, research has been done to quantify the RDD for particular fuels and fuel configurations. Some of the preliminary results of this work are shown in Table 1. It is evident from these results that shielding and fuel configuration play a significant role in the RDD. These results will be used in this analysis in two ways: to evaluate the suppression capability of the existing sprinkler system and to determine an approximate maximum heat release rate of which the sprinkler system must respond.

6.2.2 System Capability

A hydraulic analysis of the sprinkler system indicated that a single open sprinkler will supply approximately 0.39 gpm/ft². A remote area of 1500 ft² with 13 open sprinklers was shown to be capable of delivering 0.31 gpm/ft² at the most remote sprinkler. The other 12 sprinklers would have a higher density which would not exceed 0.39 gpm/ft². This available water density is sufficient to extinguish fires from burning fires which have a configuration similar to upholstered furniture or wood cribs, i.e., little shielding, with heat release rates at least on the order of 2000 kW. As a matter of fact, the results of the full scale tests discussed in the literature search indicate that such fuels, growing at a rate comparable to the ultra-fast t² growth rate can be readily extinguished at a critical heat release rate of 2000 kW with a water density of 0.12 gpm/ft². Therefore, the available water density of 0.31 gpm/ft² provides a significant safety factor relative to water supply for extinguishing these types of fuels, providing the system responds before the fire size exceeds the critical heat release rate.

The plastic commodity represents a high challenge fire because of the high degree of shielding, and to a lesser degree the higher heat of combustion of plastic materials compared to ordinary combustibles. Test fires in the plastic commodity fuel were shown to have a growth rate which could

be approximated as ultrafast and peak heat release rates which approached 3900 kW. Only when the RDD was increased to the 0.35 to 0.45 gpm/ft² range was extinguishment possible. And, in these cases, the critical heat release rate at water application was much smaller, on the order of 500 kW. Had the response of the sprinklers been delayed and the heat release rate of this fuel exceeded 500 kW by any appreciable amount, it is not certain that this water density would have been sufficient.

The fuel packages which were observed during the site survey appeared to have material characteristics and geometries that would result in incidental fires of intensities and duration less than or equivalent to those of the upholstered furniture or wood cribs. The fuels were located in the open, and were not shielded or obstructed by other fuels or equipment to any significant degree.

6.3 Sprinkler Response Time

6.3.1 The Concept of Sprinkler Response

The time required for the sprinkler to respond to a given fire depends on the RTI (e.g., response time index -- a measure of thermal sensitivity) of the sprinkler, its distance from the heat source, and the burning characteristics of the heat source. To reduce the response time of a system, it can be designed with reduced spacing or with sprinklers with a lower RTI. The sprinklers with the lowest RTI for use in an industrial occupancy are quick response (QR) sprinklers which typically have an RTI of approximately 50 (ft.s)^{1/2}.

6.3.2 Response Modeling

The computer model DETACT was utilized to determine the approximate response times of the sprinklers in Building 707. Two locations and two sprinkler types were considered. The two locations were (1) the baseline where the sprinklers are located at the ceiling prior to its removal, and the other location is with the sprinklers located at the actual Module ceiling, 17.5 ft above the floor. The two sprinkler types considered were a standard sprinkler with a response time index (RTI) of approximately 250 (ft.s)^{1/2}, and a quick response sprinkler with an RTI of approximately 50 (ft.s)^{1/2}.

6.3.3 Baseline Response Modeling

The baseline performance of the sprinkler systems in the Modules of Building 707 must be evaluated before any conclusions can be made about the effectiveness of the heat collector. The baseline is defined as the condition which

existed prior to the removal of the suspended ceiling. The performance of the sprinkler systems was evaluated in terms of response time and suppression capability.

The response time of a sprinkler is related directly to the sensitivity of the sprinkler and factors associated with the heat source. These factors include the height of the sprinkler above the fire, the horizontal distance from the fire, and geometry considerations such as obstructions and ceiling configuration.

6.3.3.1 Standard Response Sprinkler

Table 8 provides a summary of the calculated sprinkler response times for steady heat release rates of 200, 500, 1000 and 1500 kW at horizontal distances of 0, 2, 4, 6 and 7.8 ft from the fire, and a standard response sprinkler with an RTI of 250 (ft·s)^{1/2}.

Based on results from the computer simulation, the minimum constant heat release rate necessary for a sprinkler to respond at all in the case of the baseline system is 141 kW. This value is for the case of the sprinkler directly over the fire. It should also be noted that the actual response time would probably be excessive. As shown in Table 8, the minimum heat release rate for sprinkler activation when the fire is located midway between sprinklers (radius = 7.8 ft) is greater than 500 kW, with the response time being approximately 105 s at 1000 kW. It must be kept in mind when considering these values that they do not account for any fuel geometry or shielding factors and they assume a steady heat release rate.

An alternative assumption for the heat release rate is one which starts at zero and grows geometrically to some maximum value, as shown graphically in Figure 8. A typical approach is to assume that the change in heat release rate will be proportional to the square of time, t^2 . Using this approach involves the use of a proportionality constant. This constant ranges from 0.0469 to 0.1876 kW/s² which corresponds to a fast and ultrafast fire, respectively. Table 9 shows the results of using a fast and ultrafast fire as the fire input data for DETACT. At the maximum distance from the sprinkler, 7.8 ft, the response time for a standard sprinkler was predicted to be approximately 180 and 113 seconds for the fast and ultrafast fires, respectively. These times correspond to heat release rates of 1519 and 2395 kW, respectively.

Table 8. DETACT Baseline Sprinkler Response Time Predictions
 Sprinkler Located at False Ceiling, 12 ft Above
 Fuel, RTI = 250 (ft.s)^{1/2}

<u>Radius, ft</u>	<u>200 kW</u>	<u>Time to Reach 165°F, s</u>		
		<u>500 kW</u>	<u>1000 kW</u>	<u>1500 kW</u>
0	116.3	37	19.5	13.9
2	120.1	38.2	20.1	14.4
4	NR*	92.2	42.3	28.8
6	NR	196.4	71.7	46.4
7.8	NR	NR	105.1	65.2

* NR - Not reached

Table 9. DETACT Baseline Sprinkler Response Time Predictions
 Sprinkler Located at False Ceiling, 12 ft Above
 Fuel, t² Growing Fire, RTI = 250 (ft.s)^{1/2}

<u>Radius, ft</u>	<u>Time to Reach 165°F, s</u>	
	<u>Fast Fire</u>	<u>Ultrafast Fire</u>
0	100.8	64.5
2	101.8	65.2
4	135.5	85.2
6	160.8	100.8
7.8	180.0	112.5

Figure 8 t^2 fire growth rates

The results of the cases modeled with the DETACT program indicate that with standard sprinklers, RTI approximately $250 \text{ (ft}\cdot\text{s)}^{1/2}$, the response time ranges from 105.1 s, assuming a steady heat release rate of 1000 kW, and 180 s, assuming a fast, t^2 , growing fire. The heat release rate at the time of sprinkler activation for the fast fire was 1519 kW. Assuming a steady heat release rate of 1519 kW with everything else remaining the same, gives a response time of 65.7 s. From these results, it appears that the baseline system had the capability to respond to a fire with a heat release rate of approximately 1000 to 1500 kW with a response time of between approximately 105 and 66 s. These estimates assume no obstructions and a smooth ceiling. Obstructions to the fire plume or a non-smooth ceiling will cause the response time to be different, and most likely greater.

6.3.3.2 Quick Response Sprinkler

The modeling results for the quick response sprinkler, RTI approximately $50 \text{ (ft}\cdot\text{s)}^{1/2}$, are shown in Table 10 for the baseline condition at heat release rates of 200, 500, 1000 and 1500 kW, and at horizontal distances of 0, 2, 4, 6 and 7.8 ft. Table 11 shows similar results for a fast and ultrafast t^2 growing fire.

The results indicate that at the maximum distance from the sprinkler of 7.8 ft, the response time to a steady 1000 kW fire will be approximately 24 s. The response time for the two growing fires ranged from approximately 127 to 300 s for the fast and slow fires respectively. These times correspond to a heat release rate of 756 and 593 kW respectively. The response time of a quick response sprinkler to a steady 756 kW fire was predicted to be approximately 33 s. Therefore, it is expected that a quick response sprinkler installed in the baseline system would respond to a fire with a heat release rate range of 750 to 1000 kW with a response time range of 24 to 33 s.

The baseline results are summarized in Table 12. The fast t^2 growing fire results will be used in the remaining analysis, providing a relatively conservative result. The design of the heat collector will be considered equivalent to the baseline if it is shown that these or better response times can be achieved.

6.3.4 Sprinklers at Module Ceiling Response Modeling

6.3.4.1 Standard Response Sprinkler

The same procedure and input used for the baseline modeling was used for this case, except that the height between the sprinkler and the fuel was increased from 12 to 17.5 ft. Table 13 shows the results of the DETACT runs for

Table 10. DETACT Baseline Sprinkler Response Time Predictions,
Sprinkler Located at False Ceiling, 12 ft Above
Above Fuel, RTI = 50 (ft.s)^{1/2}

<u>Radius, ft</u>	<u>Time to Reach 165°F, s</u>			
	<u>200 kW</u>	<u>500 kW</u>	<u>1000 kW</u>	<u>1500 kW</u>
0	26.5	10.5	6.8	5.7
2	26.9	10.6	6.9	5.8
4	NR*	21.4	11.4	8.7
6	NR	42.2	17.2	12.2
7.8	NR	NR	23.9	16.4

* NR - Not reached

Table 11. DETACT Baseline Sprinkler Response Time Predictions
Sprinkler Located at False Ceiling, 12 ft Above
Fuel, t² Growing Fire, RTI = 50 (ft.s)^{1/2}

<u>Radius, ft</u>	<u>Time to Reach 165°F, s</u>	
	<u>Fast Fire</u>	<u>Ultrafast Fire</u>
0	69.6	39.6
2	70.1	39.9
4	93.3	53.4
6	112.3	64.3
7.8	126.7	72.3

Table 12. Result Summary of DETACT Modeling of Baseline
System with Standard and Quick Response
Sprinklers

Standard Sprinkler		
<u>Threshold</u>		
<u>Heat Release Rate, kW</u>	<u>Growth Rate</u>	<u>Response Time, s</u>
1000	Steady	105
1519	Fast	180
1519	Steady	66
Quick Response		
<u>Threshold</u>		
<u>Heat Release Rate, kW</u>	<u>Growth Rate</u>	<u>Response Time, s</u>
1000	Steady	24
756	Fast	127
756	Steady	33

Table 13. DETACT Sprinkler Response Time Predictions,
Sprinkler Located at Module Ceiling, 17.5 ft
Above Fuel, RTI = 250 (ft·s)^{1/2}

<u>Radius, ft</u>	<u>Time to Reach 165°F, s</u>			
	<u>200 kW</u>	<u>500 kW</u>	<u>1000 kW</u>	<u>1500 kW</u>
0	NR*	111.3	44	29.1
2	NR	111.3	44	29.1
4	NR	233.3	65.3	41.6
6	NR	NR	127.9	72.1
7.8	NR	NR	249.7	108.9

* NR - Not reached

Table 14. DETACT Sprinkler Response Time Predictions,
Sprinkler Located at Module Ceiling, 17.5 ft
Above Fuel, t² Growing Fire, RTI = 250 (ft·s)^{1/2}

<u>Radius, ft</u>	<u>Time to Reach 165°F, s</u>	
	<u>Fast Fire</u>	<u>Ultrafast Fire</u>
0	132.7	86.6
2	132.7	86.6
4	150.2	97.4
6	178.1	115.5
7.8	196.5	129.3

Table 15. DETACT Sprinkler Response Time Predictions,
Sprinkler Located at Module Ceiling, 17.5 ft
Above Fuel, RTI = 50 (ft·s)^{1/2}

<u>Radius, ft</u>	<u>Time to Reach 165°F, s</u>			
	<u>200 kW</u>	<u>500 kW</u>	<u>1000 kW</u>	<u>1500 kW</u>
0	NR*	25.2	11.7	8.8
2	NR	25.2	11.7	8.8
4	NR	49.6	16.0	11.2
6	NR	NR	28.5	17.3
7.8	NR	NR	52.8	24.7

* NR - Not reached

Table 16. DETACT Sprinkler Response Time Predictions,
Sprinkler Located at Module Ceiling, 17.5 ft
Above Fuel, t² Growing Fire, RTI = 50 (ft·s)^{1/2}

<u>Radius, ft</u>	<u>Time to Reach 165°F, s</u>	
	<u>Fast Fire</u>	<u>Ultrafast</u>
0	101.2	57.0
2	101.2	57.0
4	114.4	64.6
6	138.5	77.5
7.8	157.3	87.3

constant heat release rate fires and Table 14 shows the results for fast and ultrafast t^2 growing fires.

The results indicate that moving the sprinklers from the baseline location 12 ft above the floor to 17.5 ft above the floor at the Module ceiling, increases the response time significantly. At the maximum distance from the sprinkler, 7.8 ft, the time required to respond to a steady 1000 kW fire increases from approximately 105 to 250 s. The response times for the growing fires increased as well. In the case of the fast growing fire, the response time increased from 180 to 217 s which correlates to heat release rates of 1519 and 2087 kW, respectively. Using a steady heat release rate of 1810 kW for this case gives a response time of 71 s at a radius of 7.8 ft.

6.3.4.2 Quick Response Sprinkler

Substituting a quick response sprinkler for the standard sprinkler used in the above modeling gives the results shown in Table 15 for steady heat release rates and Table 16 for t^2 growing fires. At the maximum distance of 7.8 ft and 1000 kW, the response time increased from 24 s for the baseline to 53 s for sprinklers at the Module ceiling. For the fast growing fire case, the response time increased from approximately 127 s to 157 s.

The results obtained for the sprinklers at the Module ceiling have assumed that the ceiling was smooth and that there were no obstructions between the heat source and the sprinkler element. It was observed during the survey of the Modules in Building 707 that there were a significant number of obstructions located in the upper part of the room and the ceiling was not smooth. The obstructions which consisted mostly of pipes and ducts were substantial and could significantly delay the operation of sprinklers by obstructing the flow of hot gases from the fire and by cooling those gases. The obstructions may also significantly impair the ability of the sprinklers to deliver water in any kind of pattern to the fuel surface, reducing the extinguishing effectiveness of the sprinklers.

7.0 DISCUSSION AND EVALUATION OF ALTERNATIVES

7.1 Heat Collectors

7.1.1 Performance Assessment

Existing plume correlations do not adequately address outer regions of a fire plume. This is where a predictive capability is needed to assess the utility of heat

Table 17. Response Times for Standard Response
(RTI = 249 (ft·s)^{1/2}) Time Constant Discs
from Full Scale Testing

		Response Time, s				
		<u>Steady Heat Release Rate, kW</u>				<u>Growing Fire</u>
<u>d*</u>	<u>r</u>	<u>150</u>	<u>200</u>	<u>500</u>	<u>1500</u>	<u>t₂ (Fast)</u>
C _L	0	ND	55	55	ND	ND
0	2.5	216	66	48	ND	ND
1	3.5	444	144-216	102	ND	144
2	4.5	NR	468-627	141-285	ND	ND
3	5.5	NR	NR	ND	180-204	ND
5.3	7.8	NR	ND	ND	576-NR	ND

*d = Distance from collector edge, m
r = Distance from collector centerline, m
ND = No data
NR = No response

Table 18. Response Times for Quick Response
(RTI = 47 (ft·s)^{1/2}) Time Constant Discs
from Full Scale Testing

<u>d*</u>	<u>r</u>	Response Time, s				<u>Growing Fire</u> <u>t₂ (Fast)</u>
		<u>Steady Heat Release Rate, kW</u>				
		<u>150</u>	<u>200</u>	<u>500</u>	<u>1500</u>	
C _L	0	ND	15	15	ND	ND
0	2.5	42	15	12	ND	ND
1	3.5	114	15-93	27	ND	52
2	4.5	900-NR	285-300	57-87	ND	ND
3	5.5	ND	540-570	222-276	72-84	ND
5.3	7.8	ND	ND	ND	213-NR	ND

*d = Distance from collector edge, m
r = Distance from collector centerline, m
ND = No data
NR = No response

collectors. For this reason, the small and full scale testing was done.

The objectives of the testing were to determine (1) the sensitivity of sprinkler response to a fire located at or beyond the edge of the collector, (2) the maximum distance from the collector edge that sprinkler response will occur, and (3) the optimum collector size. The small scale testing indicated that the collector geometry which gave the best response was a flat collector, and that no appreciable differences were found between round or square shaped flat collectors. A collector geometry which included edges was found to have longer response times and lower peak temperature signals.

The results of the full scale testing indicated that if the centerline of the fire is further than 1 to 2 ft from the edge of the collector, delays in the response of standard sprinklers (RTI greater than approximately $200 \text{ (ft}\cdot\text{s)}^{1/2}$) will be excessive. As shown in Table 17, consistent and acceptable response times were achieved only when the fire was positioned at or near the edge of the collector. At a distance of 5.3 ft from the edge of the collector, which represents the midpoint between two sprinklers for the installations in the Modules, the results indicate that the sprinklers may not respond at all for this size collector. Heating of the sprinkler or time constant disc to its response threshold can not take place because the distance between the plume centerline and the edge of the collector is sufficient to prevent or minimize formation of a heated jet under the collector.

In the case of the quick response elements, significant reductions in response time from the standard response elements were obtained as shown in Table 18. However, the response times were still excessive when the fire centerline was 3 to 5.3 ft from the edge of the collector. This indicates that in both cases the jet that was formed under the collector when the fire was positioned at this distance did not have sufficient temperature or velocity to provide acceptable, consistent sprinkler response. As with the standard response elements, at a distance of 5.3 ft there were cases where the element did not reach the activation temperature of 165°F.

7.1.2 Conclusions

The results of this study indicate that for any size heat collector, if a fire is greater than 1 to 3 ft beyond the edge of a flat collector the sprinkler may not respond, regardless of its thermal sensitivity. If a fire is located under the collector or at the edge of the collector, a

sprinkler placed in the center of the collector, will respond faster than if there was no collector. However, in this case the collector is performing the same function as a ceiling, but only one sprinkler is expected to open.

In order to assure that the sprinkler system will respond to a fire of reasonable size located between two sprinklers the collector would have to be enlarged from the test collector size of 5 ft square to 6 or 6.5 ft square. A collector of this size would occupy from 30 to 35% of the 120 ft² sprinkler coverage area and if constructed of 1/4-inch stainless steel, as the prototype was, would weigh approximately 440 lbs. Even if a collector of this size was acceptable, it would not provide sprinkler response performance equal to the systems originally installed in the Modules.

The response sensitivity of a sprinkler system is a critical factor because without a ceiling directly above the sprinkler it is most likely that only one sprinkler will respond to a fire. If the fire has grown beyond a critical size (e.g., 2000 kW) for extinguishment because the sprinkler response is delayed, the fire may continue to grow and readily spread beyond the coverage area of the single sprinkler. Using heat collectors to substitute for the ceiling has been shown to be a questionable means of providing equivalent response and protection.

7.2 Moving Existing Sprinklers

An alternative to providing a heat collector at each sprinkler is to move each sprinkler to the Module ceiling. This would provide a surface above the sprinkler which is needed to assure response. The problem with doing this is that there are other factors which could severely impair the performance of the sprinklers at this level. The main problem is the large quantity of obstructions in the form of pipes, ducts, etc. which occupy the upper volume of these Modules. These obstructions could impair the performance of the sprinklers by delaying response and interfering with the water spray distribution from the sprinkler.

The response of the sprinklers may be significantly delayed when an object is located between the fire and a sprinkler. This object will tend to absorb energy from the fire plume, reducing its temperature and buoyancy, and may deflect it from its path upward. These effects can result in longer response times even with quick response sprinklers. The large quantity of these obstructions observed in the Modules makes this problem particularly acute.

Obstructions will also interfere with the distribution of water spray from the sprinkler. This may seriously compromise the ability of the sprinklers to extinguish a fire and could result in the fire spreading and causing much greater damage. For these reasons, it is concluded that moving the sprinklers to the Module ceiling is not acceptable and would not solve the problem created by the removal of the drop ceiling.

7.3 Changing Sprinkler Sensitivity

Another alternative is to replace the existing standard response sprinklers with quick response sprinklers. Proponents of this solution may argue that if the problem is one of sprinkler response, then a sprinkler which reacts faster than the existing standard response sprinkler would be beneficial. The problem with this approach is that unless the fire is located directly below a sprinkler, it is unlikely that it will activate. This is because the sprinklers will still be 12 ft above the floor and 5.5 ft below the ceiling. The ceiling surface is a primary mechanism for providing a sprinkler with sufficient energy from a fire to activate. Without a ceiling, little confidence should be placed in the ability of these sprinklers to activate in sufficient time to affect extinguishment.

8.0 RECOMMENDATIONS

A key objective in this study was to determine the benefits of installing a flat plate or box type heat collector directly over a sprinkler to reduce sprinkler response time. If determined feasible, the study would include efforts to appropriately size the collector to meet performance requirements. The design response goal was based on the predicted response time and maximum suppressible fire size for the sprinkler systems installed in the Modules of Building 707, prior to the removal of the drop ceiling, and the fire hazard evaluation of the fuel packages observed in the Modules. The fire hazard evaluation provided peak heat release rates as well as growth rates for fires which could occur in these spaces.

Full scale testing indicated that the utility of the prototype heat collector was limited. The 5 ft square flat collector gave satisfactory performance only when the fire was located less than 2 ft from the edge of the collector when standard response sprinklers were used. If quick response sprinklers are utilized, the test results were similar. Acceptable and consistent sprinkler response was not achievable with the prototype heat collector design when

the fire was located greater than 1 to 3 ft beyond the edge of the collector.

These results are not acceptable because a fire may exist from the center of the collector to 7.8 ft from the center of the collector, and the results must consistently meet the response goal out to this distance. Moving beyond the edge of the collector introduces the possibility of significant delays in sprinkler response, which could result in the fire growing beyond the suppression capability of the sprinkler system (e.g., approximately 2000 kW). Therefore, the installation and use of heat collectors on the sprinkler systems located in the Building 707 Modules is not recommended. A collector larger than the 5 ft square prototype will give better results but it will not provide a level of protection which is equal to what existed prior to the removal of the drop ceiling.

Movement of the sprinklers to the Module ceiling is not a viable solution because of the excessive quantity of obstructions in the upper volume of these rooms and is not recommended.

Replacing the existing standard response sprinklers with quick response sprinklers in the absence of a ceiling is not an acceptable solution because there is still a probability that a fire will be located between two sprinklers. In the event that this scenario occurs, the sprinklers may not respond to the fire.

Based on the results of this study, a functional alternative to replacing the drop ceilings in these Modules is not apparent. Whether we based the decision on equal performance to the original design, or on a hazard basis relative to the fuels available and the likely fire growth rates, the several options examined appear inadequate. In view of this, we recommend replacement of the original drop ceiling.

9.0 REFERENCES

1. Installation of Sprinkler Systems, NFPA 13, National Fire Protection Association, Quincy, MA, 1989.
2. DeMonbrun, J.R., and McCormick, J.W., "Experiments with Sprinkler Head Canopies for Fire Protection," Union Carbide, Oak Ridge, TN, 1973.

3. Heskestad, G., and Smith, H., "Investigation of a New Sprinkler Sensitivity Approach Test: The Plunge Test," FMRC 22485, Factory Mutual Research Corporation, Norwood, MA, 1976.
4. Fleming, R.P., "High-on Sprinklers," Sprinkler Quarterly, National Fire Sprinkler Association, Patterson, NY, Spring 1989.
5. Heskestad, G., "Fire Plumes," SFPE Handbook of Fire Protection Engineering, Section 1, Chapter 6, National Fire Protection Association, Quincy, MA 1988.
6. Alpert, R.L., "Turbulent Ceiling-Jet Induced by Large-Scale Fires," Technical Report No. 22357-2, Factory Mutual Corporation, Norwood, MA, 1974.
7. Heskestad, G., and Delichatsios, "The Initial Convective Flow in Fire," 17th International Symposium on Combustion, Combustion Institute, Pittsburgh, PA, 1978.
8. Evans, D., and Stroup, D., "Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings," NBSIR 85-3167, National Bureau of Standards, Center for Fire Research, Washington, D.C., 1985.
9. Carey, W.M., "Report of the Quick Response Sprinkler Project, Group 2 Performance Tests, Phase I - RDD Tests," Underwriters Laboratories, Inc., sponsored by the National Fire Protection Research Foundation, Quincy, MA, 1988.
10. Standard on Automatic Fire Detectors, NFPA 72E, National Fire Protection Association, Quincy, MA, 1989.
11. Gessler, J., "SEDAN - A Computer Program for Design and Analysis of Automatic Fire Sprinkler Systems and Water Supply Systems," Gessler Group, Inc., Ft. Collins, CO, 1988.
12. Perstein, J., and Castellano, J.A., "Hydraulic Model Analysis of Water Distribution System, Rocky Flats," Hughes Associates, Inc., Wheaton, MD, 1989.
13. DiNenno, P.J., Scheffey, J.L., Gewain, R.G., and Shanley, J.H., "Fire Hazard Analysis of Rocky Flats Building 776/777 Duct Systems," Hughes Associates, Inc., Wheaton, MD, 1988.

Appendix A - Small Scale Collector Testing

1.0 SMALL SCALE TEST OBJECTIVES

The small scale tests were designed and conducted to screen selected collector geometries and to select, based on the results, the optimum type(s) for full scale evaluation.

The designs which were tested included a square flat collector, a round flat collector, a square collector with a edge around the collector perimeter, and a round collector with a edge around the collector perimeter. The edge on the square collector was at an angle of 90° to the collector and the edge on the round collector was at an angle of 45°. The square collectors were 8 in. by 8 in. and the round collectors had a diameter of 8 in. The edge on the two collectors mentioned above was 1.5 in.

2.0 TEST SET-UP AND PROCEDURE

The collectors were tested in pairs as shown in Figure A-1. They were located 3 ft above the base of the heat source. The centerline of both collectors was 8 in. from the burner plume centerline.

A brass disc 1/32 in. thick and 3/8 in. diameter was placed in the center of each of the collectors. This disc has been designed to have the same temperature response as a fast response sprinkler element. The response time index (RTI) of this disc was determined to be approximately 47 (ft·s)^{1/2}. Two Type K thermocouple wires were welded to these time constant discs and were connected to a strip chart recorder. The recorder gave a printout of the millivolt signal from the disc as a function of time.

Two different heat sources were utilized during the testing. Series 1 utilized a cotton wick which was soaked in n-Heptane. Series 2 and 3 utilized a small propane bottle to which a small diameter (1/16 in.) copper, capillary tube had been attached. Both of these gave a laminar flame which produced sufficient heat for the test. A propane plumber's torch was also used in Series 1 but it did not give the laminar, mostly buoyancy driven plume which was needed. For this reason the data from these initial tests were not used. The capillary burner was superior to the n-Heptane burner however, because once the liquid n-Heptane which was in the wick burned, the flame height decreased. The propane flame remained steady throughout the test series. To prevent room

drafts or other air movement from interfering with the plume, an enclosure was constructed around the test set-up.

The test procedure consisted of igniting the heat source which was in place between and below the heat collectors. The strip chart recorders were run continuously during the test. Once the signal from the time constant discs became steady, the heat source was removed and the discs were allowed to cool to ambient temperature before the next test run was started. All attempts were made to keep conditions as constant as possible between runs.

3.0 RESULTS

The millivolt signal verses time data from Series 2 and 3 were plotted and used to evaluate the different collectors. All of the data from Series 1 and the n-Heptane data from Series 2 were not utilized because of the momentum imparted to the plume by the torch and the non-steady output from the n-Heptane burner.

As shown in Figures A-2 through A-17 in Series 2, the peak signal from the square, flat plate was in most cases (12 of the 16 runs) greater than the square collector with the edge. The change in the millivolt signal is directly proportional to a change in temperature. The greater the peak signal, the greater the temperature. In addition, the time constant disc on the flat plate collector responded faster (10 of 16 runs) than the one on the edged collector.

In Series 3, a flat plate collector and a round collector with the 45° edge were tested. As shown in Figure A-18 through A-33, the peak signal during Series 3 from the flat plate was greater in most cases (11 of the 16 runs) than the edged collector. Also, in agreement with the Series 2 results, the time for the disc to respond in Series 3 was in most cases (14 of the 16 runs) less than that of the edged collector.

The results from the two edged collectors are shown together in Table A-1. The mean peak signal from the 45° edge collectors were greater in every run than the 90° edge collector. The response times (time to reach 0.1 mV) of the 45° edge collector were also less in every run than the response time of the 90° edge collector. These results indicate that there is a repeatable difference between the two collectors and the more rapid and higher magnitude response was provided by the collector with the 45° edge.

The results of a comparison test of a flat round collector and a flat square collector are shown in Table A-2.

The round collector had a diameter of 8 in. and the square collector was 8 in. by 8 in. This gives areas of 50.2 in.² and 64 in.² for the round and square collectors, respectively. As shown, the peak mV signals and the times to reach 0.1 mV are sufficiently close in value that a difference cannot be distinguished and no conclusion can be drawn about which is superior.

4.0 CONCLUSIONS

The results indicated that the most desirable test collector design was the flat collector. Both the 90° and 45° edged collectors which were tested had smaller peak signals and slower response times than the flat collector.

The results indicate that the edge may hinder the flow of heated gases past the time constant disc. This may be due to the formation of a zone within the collector of buoyant air, which becomes stagnant because of the confinement. The rate of energy transfer from the hot gases by convection to an element placed in the plume is proportional to the velocity of the gases moving past the element. The activation of an automatic sprinkler relies on convective heating by the flow of hot gases past it. Reducing the velocity of the gases will reduce the rate of heat transfer. The results of these small scale tests indicate that a collector without an edge will cause a greater quantity of energy to transfer to an element in the center of the collector, than a collector with an edge.

Based on these small scale tests a square, flat collector was chosen for the full scale testing.

Figure A-1 Small Scale Test Apparatus

Figure A-2 Small Scale Test Results

Figure A-3 Small Scale Test Results

Figure A-4 Small Scale Test Results

Figure A-5 Small Scale Test Results

Figure A-6 Small Scale Test Results

SERIES 2, RUN 6

Figure A-7 Small Scale Test Results

Figure A-8 Small Scale Test Results

Figure A-9 Small Scale Test Results

Figure A-10 Small Scale Test Results

Figure A-11 Small Scale Test Results

Figure A-12 Small Scale Test Results

Figure A-13 Small Scale Test Results

Figure A-14 Small Scale Test Results

Figure A-15 Small Scale Test Results

Figure A-16 Small Scale Test Results

Figure A-17 Small Scale Test Results

Figure A-18 Small Scale Test Results

Figure A-19 Small Scale Test Results

Figure A-20 Small Scale Test Results

Figure A-21 Small Scale Test Results

Figure A-22 Small Scale Test Results

Figure A-23 Small Scale Test Results

SERIES 3, RUN 7

Figure A-24 Small Scale Test Results

Figure A-25 Small Scale Test Results

Figure A-26 Small Scale Test Results

Figure A-27 Small Scale Test Results

Figure A-28 Small Scale Test Results

Figure A-29 Small Scale Test Results

Figure A-30 Small Scale Test Results

Figure A-31 Small Scale Test Results

Figure A-32 Small Scale Test Results

Figure A-33 Small Scale Test Results

Table A-1. Small Scale Test Result Summary for Collectors
With an Edge

<u>45° Edge</u>		<u>90° Edge</u>	
Peak mV	t _{0.1} mV*	Peak mV	t _{0.1} mV
0.355	27.6	0.09	NA**
0.27	18.6	0.01	NA
0.195	14.4	0.04	NA
0.26	21.0	0.09	NA
0.35	10.8	0.105	73.2
0.35	21.6	0.06	NA
0.385	13.2	0.055	NA
0.315	22.2	0.2	31.2
0.515	7.2	0.36	7.8
0.335	11.4	0.15	45.6
0.41	10.2	0.17	88.8
0.435	14.4	0.03	NA
0.3	12.6	0.13	84.0
0.35	12.6	0.205	19.2
0.36	12.0	0.19	36.6
0.36	15.6	0.325	16.8

* t_{0.1} mV = time to reach a 0.1 mV signal

** NA = not achieved

Table A-2. Small Scale Test Result Summary for Round
and Square Flat Collectors

<u>Round</u>		<u>Square</u>	
Peak mV	t _{0.1} mV	Peak mV	t _{0.1} mV
0.35	7.8	0.38	5.1
0.42	10.2	0.39	9.7
0.525	7.2	0.41	8.1
0.44	7.8	0.40	7.6
0.46	10.8	0.44	11.2
0.495	6.6	0.47	7.2
0.44	9.6	0.435	8.5
0.57	7.8	0.52	7.5
0.215	18.0	0.20	16.3
0.25	18.0	0.26	17.4
0.32	14.4	0.33	14.0
0.355	10.2	0.34	11.3
0.46	12.0	0.45	11.2
0.44	10.2	0.32	10.7
0.35	14.4	0.39	13.2
0.50	7.8	0.435	7.6

DATE

FILMED

9/20/94

END