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AFAPL-TR-78-84

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**APPLICABILITY OF FIBER OPTICS TO  
AIRCRAFT FIRE DETECTION SYSTEMS**

*HTL INDUSTRIES, INC.  
K WEST DIVISION  
SANTA ANA, CALIFORNIA 92704*

OCTOBER 1978

TECHNICAL REPORT AFAPL-TR-78-84  
Final Report for Period May 1973 -- August 1978

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

<b>19 REPORT DOCUMENTATION PAGE</b>		<b>READ INSTRUCTIONS BEFORE COMPLETING FORM</b>	
<b>18</b> REPORT NUMBER AFAPL RTR-78-84 ✓	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) <b>16</b> APPLICABILITY OF FIBER OPTICS TO AIRCRAFT FIRE DETECTION SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED Technical Report May - August 1978	
7. AUTHOR(s) <b>10</b> Richard D. McGunigle, Howard W. Jackson Robert R. Beavers		6. PERFORMING ORG. REPORT NUMBER HTL K West D-1530 ✓	
9. PERFORMING ORGANIZATION NAME AND ADDRESS HTL Industries, Inc., K-West Division 2221 South Anne Street Santa Ana, CA 92704 411 048		8. CONTRACT OR GRANT NUMBER(s) <b>15</b> F33615-78-C-2030 ✓	
11. CONTROLLING OFFICE NAME AND ADDRESS AFAPL/SFH WAFB OH 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS PE 62203F <b>16</b> PROJ/TASK/WU 30480785 <b>17</b> 87	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) <b>12</b> 73 PI /		12. REPORT DATE <b>11</b> OCTOBER 1978	
16. DISTRIBUTION STATEMENT (of this Report)  Approved for Public Release; Distribution Unlimited.		13. NUMBER OF PAGES 56	
17. DISTRIBUTION STATEMENT (of the abstract entered in Distributions 1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845, 846, 847, 848, 849, 850, 851, 852, 853, 854, 855, 856, 857, 858, 859, 860, 861, 862, 863, 864, 865, 866, 867, 868, 869, 870, 871, 872, 873, 874, 875, 876, 877, 878, 879, 880, 881, 882, 883, 884, 885, 886, 887, 888, 889, 890, 891, 892, 893, 894, 895, 896, 897, 898, 899, 900, 901, 902, 903, 904, 905, 906, 907, 908, 909, 910, 911, 912, 913, 914, 915, 916, 917, 918, 919, 920, 921, 922, 923, 924, 925, 926, 927, 928, 929, 930, 931, 932, 933, 934, 935, 936, 937, 938, 939, 940, 941, 942, 943, 944, 945, 946, 947, 948, 949, 950, 951, 952, 953, 954, 955, 956, 957, 958, 959, 960, 961, 962, 963, 964, 965, 966, 967, 968, 969, 970, 971, 972, 973, 974, 975, 976, 977, 978, 979, 980, 981, 982, 983, 984, 985, 986, 987, 988, 989, 990, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000)		15. SECURITY CLASS. (of this report)  UNCLASSIFIED	
15a. DECLASSIFICATION DOWNGRADING SCHEDULE			
18. SUPPLEMENTARY NOTES <b>14</b> HTL-K WEST D-1530 /			
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Fiber Optics Ultra-Violet Fire Detection Optics			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A review of the state-of-the-art in ultra-violet conducting fiber optics and related system components was conducted with the objective of evaluating their potential applicability to solar blind, UV fire detection systems. From this basis, conceptual systems were developed and analyzed to assess the potential payoff of incorporating optical enhancement to improve the performance, and reduce the initial and life cycle cost, size and weight of such systems, and to effect detector circuit simplification and improvement in system reliability.			

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

411 048

411 048

## FOREWORD

This report was prepared by HTL K WEST, Santa Ana, CA., under USAF Contract No. F33615-78-C-2030. The contract was initiated under Project 3048, "Fuels, Lubrication and Fire Protection", Task 304807, "Aerospace Vehicle Hazard Protection". The program was administered under the direction of the Air Force Aero Propulsion Laboratory, with G. Trask Beery, AFAPL/SFH as program manager.

This report is a summary of work completed on this contract during the period May 15, 1978 through August 15, 1978. The report was submitted in September 1978.

Appreciation is expressed by the authors to Mr. Terry M. Trumble of the Air Force Aero Propulsion Laboratory's Instrumentation Division, to the McGraw-Edison Company, and to Curt Deckert and Associates, for their consultation in the areas of establishing flame detection criteria and optical systems analysis.

SEARCHED	INDEXED
SERIALIZED	FILED
AUG 15 1978	
AFAPL/SFH	
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## EXECUTIVE SUMMARY

A review of the state-of-the-art in ultra violet conducting fiber optics and related system components was conducted with the objective of evaluating their potential applicability to solar-blind, UV fire detection systems currently under development by the Air Force (Advanced Development Plan PE 63246F, Work Unit 23480102). From this basis, conceptual systems were developed and analyzed to assess the potential payoff of incorporating optical enhancement to improve the performance, and reduce the initial and life cycle cost, size and weight of such systems, and to effect detector circuit simplification and improvement in system reliability.

Ultraviolet fiber optics technology has advanced considerably since 1967, primarily in the production of high-quality quartz fibers, as well as in related input/output optics suitable for use in the UV region above 280 nanometers ( i.e. above the "solar blind" UV region). However, such advancements have been markedly in the low packing fraction, long wavelength, low temperature applications areas (suitable for ambient temperature applications below 240°C) due to the lack of demand for higher temperature applications to date. The primary thermal limitation of such components is in the area of fiber cladding materials and techniques (generally plastics), although higher temperature materials for claddings have been evaluated, but not produced in quantity. The cost of suitable (but low temperature, low loss) clad fibers of extended lengths for use below 280 nm and in a variety of diameters suitable for aircraft fire detection system application has been significantly reduced (to below \$3.00 per meter length). The extension of these technical advancements to produce suitable high temperature, low loss fibers/bundles is not deemed to require major advancements in the state-of-the-art, and is more associated with a demand for such materials on the present manufacturers.

Using existing (or slightly extrapolated) fiber optics technology, several fire detection system concepts were evaluated and compared with a "bare (UV) detector tube" baseline system to assess the potential payoffs of incorporating fiber optics into advanced fire detection system design. The results of these analyses show that - given the limited advancements necessary to produce high-temperature, low loss fiber optics and compo-



nents at reasonable cost - significant improvements could be made in system performance (better fire detection coverage, higher reliability, lower false alarm rates) while simultaneously reducing overall system initial and life cost, weight and space requirements - primarily by increasing the number of fiber optically coupled fire detection sensor heads while reducing the number of UV detector tube assemblies required per aircraft installation.

A follow on program is recommended for the necessary developments in higher temperature, low loss fiber optics technology and their integration into high-performance fire detection systems.

SECTION I  
INTRODUCTION

The Air Force first considered the use of ultraviolet transmitting fiber optics in the mid-1960's<sup>1/</sup>, but has deferred further detailed considerations of this technology pending the development, demonstration and testing of suitable "solar-blind"<sup>\*</sup> ultraviolet detectors and related electronic sub-systems capable of sensing and reliably alerting aircraft crews to on-board fires. Subsequent to the recent fire detection tests of such solar-blind U.S. made UV fire detection systems<sup>2,5/</sup>, this study was undertaken to update the technical data on UV fiber optics and related components, and to consider the potentials for incorporating fiber optics into the present Advanced Aircraft Fire Detection Systems development program.

The incentives leading to the present study have been:

- a. The development (and manufacture) of basic UV-capable fiber optics.
- b. The relatively high thermal, weight, volume, and cost sensitivity of "bare detector"<sup>\*\*</sup> UV fire detection systems when operated in advanced aircraft environments.
- c. A need for more complete fire-sensing area/volume coverage in advanced aircraft.
- d. The potential payoffs in fire detection systems using fiber optics, including cost, weight and space reductions.

This study updates the data on the technology of fiber optics, and its applicability to improved fire detection systems for advanced aircraft.

### 1.1 Background

In 1966, the Illinois Institute of Technology Research Institute (IITRI), under the sponsorship of the Air Force Aero Propulsion Laboratory, first demonstrated the general feasibility

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\* UV detectors operating in the range below 280 nanometers wavelength, i.e. below the range of atmospheric penetrating UV solar radiations.

\*\* Any system using UV sensitive sensors alone without optical enhancement.

of using specialized fiber optics in the ultraviolet region for the detection of flames.<sup>1/</sup> While the criteria for "solar-blind" UV fire detection systems had not yet been established, the IITRI program was able to demonstrate that carefully selected materials could be extruded and clad into fibers of sufficient length to be of interest in fire detection systems. While the fibre cladding material selected by IITRI (magnesium fluoride) for their quartz fibers was compatible with aircraft environmental conditions, the IITRI-demonstrated bundles failed to satisfactorily transmit ultraviolet radiation below 250 nanometers wavelength. Nevertheless, the feasibility of "piping" ultraviolet radiation from potential fire sources to suitable UV detectors stirred the interest of aircraft fire detection system designers. But it has remained on the "back-burner" ever since, awaiting the development of solar-blind UV detector technology.

Over the decade since the IITRI program was completed, fiber optics capable of conducting wavelengths shorter than 280 nm have been developed, but generally for applications (e.g. communications, space, medical probes, etc.) other than aircraft fire detection with its attendant severe environmental conditions. During the intervening years, quartz-based fibers employing various cladding materials (usually selected to enhance transmittance and reduce the cost of single fibers, but without stringent environmental requirements such as those found in aircraft, such as elevated temperatures, chemical contamination, acoustic noise, vibration, shock, altitude and reliability/maintainability considerations) have not only been developed but are in general production. Little or no incentive has been offered to fiber optics developers/manufacturers to consider seriously the requirements for their product's applicability to more stringent environments such as those encountered aboard high-performance aircraft.

The development of solar-blind ultraviolet detectors and suitable electronic sub-systems to employ them effectively has been a long and technologically taxing process. Although a basic capability to detect ultraviolet radiation was demonstrated early, the ability to desensitize UV detectors to solar spectral radiation has required both technological and manufacturing advances far beyond original expectations. The present generation of gas-discharge type solar-blind UV detectors has met the

original criteria established by the Air Force for fire (flame) detection apparatus - with only two apparent limitations, each of which suggest a reconsideration of the application of fiber optics to such systems.

The highly sensitive solar-blind detectors tend to be both voltage and temperature sensitive, i.e. in order to meet the UV radiation sensitivity requirements in the "solar-blind" (200 to 280 nm) portion of the spectrum, the sensors must operate on a near-cascade threshold basis where thermal, cosmic, and other "ambient" forms of electromagnetic radiation tend to trigger their operation (generating false alarms), or, if desensitized against such false triggering, lower their sensitivity to true UV (flame emitted) radiation. Consequently, it is deemed desirable to isolate the UV detectors from such undesirable ambient conditions (while still maintaining their high UV sensitivity). One seemingly-reasonable method of accomplishing this is by "piping" the UV radiation emitted by flames to thermally and radiation shielded UV detectors.

Another incentive for a re-examination of UV fiber optics is the fact that the use of "bare detector" schemes requires the use of a significant number of relatively expensive, moderately large and weighty, high voltage supplied detectors throughout the aircraft fire-potential areas (e.g. engine nacelles, fuel tanks and feed lines, weapons or cargo compartments, etc.). Each such detector head installation, and its attendant electrical cables and interconnections must be electrically shielded, thermally protected, and even hydraulically insulated (as in the case of firewall throughputs). As aircraft designs tend to become more and more complex, with void spaces becoming further isolated from each other, the need for larger numbers of small volume scanning, independent fire sensor installations increases. And so, commensurately, does the cost, weight and space penalties associated with such installations if present technology (i.e. "bare detectors") is employed.

One method of reducing such penalties, while achieving more complete coverage, would be to locate the UV detector elements in lower ambient temperature/radiation regions (e.g. in engine pylon or airframe structures) and "pipe in" the UV radiation generated by flames from a number of potential fire areas. Such an approach, in concept, could conceivably reduce not only the false alarm rate, but simultaneously increase the number of areas "viewed" by each detector (perhaps trading off the number of

detectors with multiple fiber optic sensor heads), thus reducing size, weight and cost of the overall fire detection system.

Such concepts, along with the review of the state-of-the-art of fiber optic system component technology, are evaluated in the present study and report.

## 1.2 Scope

This study undertakes to review and evaluate the advancements in the state-of-the-art of UV fiber optics over the past decade (since the pioneering IITRI study), and to assess this technology in terms of its potential applicability to aircraft fire detection systems. Due to the limited nature of this effort, no attempt could be made to conduct experiments or make empirical measurements on fiber optics or components available from a variety of potential sources. This study is, therefore, limited to the use of written or verbally communicated data supplied by such sources or from the generally available literature contained within the resources at the authors' disposal.

Similarly, this effort has been necessarily limited in the degree of sophistication of the analyses that could be performed (largely by the limitations of available, usable data) on conceptual fiber optic-coupled systems. Thus, no attempt could be made to assess the applicability of fiber optic-coupled fire detection systems to any specific aircraft; yet the generic treatment used is believed to be a valuable guide to the future development of such systems.

In this report, the term "fiber optics" is used to describe commercially available or in-development, flexible, optical means suitable for the transmission of ultraviolet radiation (as from remotely located fire area) to ultraviolet (solar-blind) sensitive detectors and their associated electronics.

Similarly, this study was limited to accepting two basic premises for its evaluation: the input flame source for all fiber optics systems comparisons was considered to be that of the MIL-D-27729A "5 inch pan fire", while the fiber optic systems outputs were considered to be fed into a standard UV detector tube and its related electronics (for comparison purposes, a McGraw-Edison MK II detector system as described in a recent report<sup>3/</sup>). Although several suggestions are made on potential ways

of enhancing the optical coupling between the output of suitable fiber optics systems and the UV detector system tubes, the scope of this report did not allow the coordination of these concepts with McGraw-Edison, or other UV fire detection system sources.

Without implying any criticism whatsoever of either the McGraw-Edison or other UV detection systems presently in existence or under development or evaluation, the authors limited their analysis of potential cost, weight, and space savings potentially realizable through the use of fiber optics coupling techniques to the prototype fire detection systems recently built by McGraw-Edison<sup>3/</sup> and tested for the Air Force<sup>4/</sup> and the Federal Aviation Administration<sup>5/</sup>.

### 1.3 Evaluation Criteria

Every attempt has been made within the scope of this study to assess the applicability of the broadly-interpreted class of flame-to-detector optical coupling techniques to the environments associated with their application to high performance aircraft. While no specific set of criteria specifications were provided by the sponsors of this effort, a set of criteria largely based on the current Advanced Aircraft Fire Detection System (AAFDS) request for proposals (RFQ F33615-77-R-2029)<sup>6/</sup> was developed and used. Table 1 reflects these requirements.

Many of the criteria reflected in the current USAF AAFDS guidelines had to be interpreted (or interpolated) for this study since the current efforts did not incorporate fiber optics concepts. For example, computational analysis required the use of a photometric equivalent of the MIL-D-27729A "pan fire" specified for empirical testing of AAFDS hardware systems. Similarly, we applied the requirements for detector head temperature and flame exposure conditions to the fiber optics "links" while allowing the removal of the temperature sensitive UV detectors themselves to cooler areas. Finally, we interpreted the AAFDS system flame detection criteria (to "detect a 5 inch diameter pan fire of JP-4...at 4 feet distance ...under direct sunlight conditions..") as a definition of the detectivity of the associated UV detection system (e.g. McGraw-Edison) used as the output for all fiber optic subsystems considered. In this sense, the output UV flux delivered by the fiber optic subsystem to the UV detector

TABLE 1

AAFDS UV DETECTOR/SENSOR REQUIREMENTS

Specification for:	AAFDS Requirement	Estimated Ability to Meet AAFDS Specifications "Bare Detector" Systems	Optically Coupled Systems
Temperature, operating	-54 to +260°C ambient	Tube degrades above 230°C (400°F) → false alarms	Currently available fibers rated at/below 250°C
Flame test	5 minutes in 1093°C flame will not imbalance system operation	Good to excellent (if no electrical shorts)	Excellent (electronically isolated)
Vibration/Shock	Spectrum specified to 10G @ 500Hz	Good to excellent	Good (although no specific data available)
Mechanical	High reliability/performance under Military operating/installation/maintenance conditions	Excellent (meets MIL SPECS)	Good (if MIL SPECed via special fiber shielding). Most sensitive to bends.
Chemical	Impervious to aircraft fluids, fumes, materials	Excellent (MIL SPECed)	Excellent (if MIL SPECed)
Flame Detectivity	Meet MIL-D-27729A (detect 5" JP-4 pan fire at 4 feet)	Good (meets spec)	Can exceed spec. if optics employed to increase gain
UV test source	Provide in each sensor/detector head	Good (meets spec), but requires separate UV (electrical) source for each head	Fiber-fed centrally generated UV signal to provide "2 way test" of each cable, sensor head
Field of view angle	80° minimum	Good (meets spec)	Can exceed spec (to 180°+) depending on optical input design
Radiation (UV) interaction between sensors/detectors	Non-interactive	Could be problem if detectors "see" each other (self generated UV in tubes)	Excellent (each sensor optically isolated from all others; detector may be shielded & isolated)
Altitude	To 80,000 ft. equivalent pressure	Excellent (meets MIL SPEC)	Excellent (if MIL SPECed)

tube(s) must be the same (or greater) as that which the UV detector tube system would have received in viewing the "MIL-STD pan fire" directly (without the aid of the fiber optics).

Section II of this report reviews the state-of-the-art of UV fiber optics technology (including fibers and fiber bundles; input, output and interconnecting optics including fan-in and fan-out techniques - and their optical, mechanical, and chemical characteristics relevant to aircraft fire detection system applications). Section III explores the fire detection system applications of such fiber optic system elements and includes comparative analyses of such systems' characteristics and tradeoffs in terms of performance, reliability, cost, weight and space. Conclusions drawn from this study, and recommendations based thereon are contained in Section IV.



## SECTION II

### 2.1 GENERAL CONSIDERATIONS AND CRITERIA

Based on the foregoing discussion, the concept of UV fiber optics can be of value to the task of detecting aircraft fires if it can accomplish the following tasks:

1. Capture an acceptable number of UV photons from a jet-fuel fire at a reasonable distance; either unaided or with optical assistance.
2. Transmit these photons to a detector located in a more benign environment with acceptable attenuation or loss.
3. Endure the specified aircraft environments without failure or degradation.
4. Provide the foregoing within acceptable limits of cost, size, weight, logistics maintainability, etc.

In order to evaluate the state-of-the-art in UV fiber optics, it is necessary to convert these requirements into the applicable parameters used to describe fiber optics. In this section, a brief summary of the pertinent parameters will be provided to aid in the comparison of currently available fiber optics.

Item 1 of our requirements is dependent on two parameters. If a fiber is to capture the radiation from the fire without optical assistance, the number of photons captured is simply proportional to the effective area of the central core of a single fiber, or the sum of the core areas of the fibers in a bundle. Since each fiber is surrounded by cladding, the effective area of a bundle will be less than the total area by the packing factor.

If optical enhancement is being considered, the effective area of the lens system now replaces that of the fiber. However, the fiber still limits the effective area of the lens through a parameter known as the Numerical Aperture (N.A.). The Numerical Aperture of the fiber is directly related to the angle of view of the fiber. Surprisingly, the N.A. is not a function of the fiber geometry, rather it is only dependent on the refractive index of the core and of the cladding ( $N.A. = \sqrt{n_1^2 - n_2^2}$ ). For most commercially available fibers, the acceptance angle ( $\sin^{-1} N.A.$ ) runs from 10 to 20 degrees. This puts a serious limitation on the design of optical systems.

Item 2 is governed by the attenuation of the fiber at the wave-

lengths of interest. Since the attenuation losses increase geometrically with the length of the fiber, this parameter is best referred to in dB per meter (where dB is  $10 \log_{10} P_{out}/P_{in}$ ). The resultant decrease in intensity at the detector must be dealt with by improvements in other parts of the system.

Item 3 relates to all of the environments applicable to the present "bare detector" gas discharge tube concept. However, the most serious limitation is operating temperature. This report treats the use of fiber optics to provide an alternate system to that required by the Air Force's Program For An Advanced Fire Detection System,<sup>6/</sup> so we have adopted the temperature requirements of that document. Therefore, fibers must be capable of operating at 260°C for unlimited time, and must be capable of withstanding a 1093°C flame for five minutes without affecting the operation of other portions of the system (although, presumably, that portion of the system exposed to the fire would, itself, be destroyed or rendered incapable of further operation).

Item 4 is dependent on a number of fiber optics parameters. Cost is most important, but such things as bend radius, available connectors, automatic self-test, and mounting constraints are necessary considerations.

A review of the report, "Ultraviolet Fiber Optics for Fire and Explosion Detection"<sup>1/</sup> provided a baseline as of 1966 for the present study. The goal of the ITRI study was to fabricate fibers which transmitted UV in the range of 2000 to 3000 Angstroms, and which could withstand temperatures of 1000°F. The program determined that the only viable materials for this application were Suprasil (Quartz) for the core and Magnesium Fluoride ( $MgF_2$ ) for the cladding. The report gives a detailed account of the fabrication processes required to obtain 12.5 ft lengths of the 3 mil diameter fibers. The materials chosen resulted in a theoretical N.A. of .5 to .6 ( $\theta_{NA} = 30^\circ-37^\circ$ ), and a theoretical (bulk) attenuation of -2.1dB/m (equivalent to a transmission coefficient of  $.61^L$  where L is in meters) @ 250nm. The bulk attenuation theoretical values were comparable to the measurements made on the bulk samples used in the program. However, on the fabricated fiber bundles, the attenuation ranged from -8.3 dB/m (for uncoated fibers) to -18.5 dB/m (for thick coated fibers) all at 250nm. (As a benchmark, at 550nm the attenuation for bulk and for uncoated fibers, is -.5dB/m, and for coated fibers the attenuation is -4 to -4.7 dB/m.) No experimental verification of N.A. was cited in the report.

The conclusion of the IITRI report was that "...feasibility of fiber optics for UV fire detection was demonstrated..." although the high attenuation at wavelengths shorter than 250nm was admittedly a significant problem. Since no overall system performance figures were developed, the claim of "feasibility demonstration" seems to be mostly conjecture. Rather, it seems that the effort resulted in several prototypes of one type of UV optical fiber which, if several problems could be resolved, could provide a 1000°F UV fiber capability, which would have potential application to aircraft fire detection systems.

The IITRI effort culminated in the construction of several UV fiber optics bundles, since there were no available equivalent fibers on the market at that time. By 1978, however, the use of fiber optics for data transmission has progressed to the point where availability of commercial fibers which are reasonably good transmitters of ultraviolet in the 200-280nm range are generally available. This has come about largely, however, as a byproduct of the industry's quest for lower and lower attenuation in the visible and infrared regions of the spectrum. Almost every manufacturer of fibers now offers a family of UV transmitting quartz core fibers. They all seem to be clad with a silicate or fluorocarbon material, which would indicate an upper temperature limit of approximately 250°C. This particular choice of core cladding results in a rather low numerical aperture (full acceptance angle of approximately 16°) which restricts the design of optically coupled systems to some degree. In addition, discussions with most fiber manufacturers indicates that they are not too confident of the core to cladding bond at elevated temperatures. This seems to be a process related problem, and they believe that there is no inherent restriction on the use of these fibers up to the limit of the fluorocarbon materials used (some 240°C).

The presently available fiber optics fall into two distinct groups. There is still a great deal of activity in bundles of fine (.003 inch diameter) fibers similar to those produced at IITRI in the mid 1960's. In addition, there are now available single fibers which range up to 0.04 inch diameter. In every case, the outside protective jacket would have to be redesigned for suitability in an aircraft environment, but this would not affect the critical core and cladding process which results in relatively high trans-

mission coefficients in the ultraviolet region. These processes are continually being improved due to the high interest in fiber optics for data transmission, and this can greatly benefit the advanced Aircraft Fire Detection System application. However, there seem to have been no further efforts (since 1967) to develop very high temperature fibers, e.g.  $MgF_2$  clad quartz, such as those originally investigated at IITRI.

#### Currently Available Fibers

The results of our survey of UV fiber optics manufacturers is summarized in Table 2. The current manufacturers and suppliers of fiber optics are not aggressively pursuing fibers specifically for application in the ultraviolet spectrum. Thus, the transmission and numerical aperture data applicable to the UV region may not be as reliable as is desired. A later portion of this section deals with the interpretation of that range of data and how the nominal performance characteristics for Section III of the report were derived.

An additional complication arises from the fact that some of the fiber assembly manufacturers obtain their basic clad fibers from sources in Europe. Schott and Quartz et Silice fibers are sold through American manufacturers who simply provide a protective sheathing, but Fort (of France) is not represented in this country to our knowledge.

Figure 1 depicts the published transmission data for applicable fibers in the ultraviolet range. There seems to be a fair degree of scatter in the UV data between vendors. Some of this probably related to the methods used for testing. The most thorough treatment of published data is given by Schott<sup>7/</sup>. Their data lies midway between the extremes of the other manufacturers data. Therefore, we have used a nominal attenuation of .81 dB/m at 250nm, midway between Schott's data points for single fibers and bundles. This equates to the .83<sup>L</sup> transmission coefficient used in Sect.III of this report. It should be borne in mind that the steep slopes of the attenuation vs wavelength curves could affect the final outcome of the actual system performance viz a viz calculations made using manufacturers data. For example, if the Quartz et Silice fiber (distributed by Quartz Products Corporation in the U.S.) data is used, the attenuation jumps from 0.31 dB/m to 4 dB/m at 250nm. In practice, this results in a transmission through a 5 meter length of fiber of 39% for Schott and 1% for Q&S (at 250nm). Further, if the effective mean wave-

length for an operating system is closer to 225nm than 250nm, the transmissions for the same two cases would become, 14% for Schott and .003% for Q&S. However, the JP-4 flame emission data developed by Linford, Dillow, and Trumble<sup>8/</sup> suggests that the mean spectral frequency of interest is in the 250 nm range. Such variability in the data strongly suggests the need for precise measurements as a part of any fiber optics development program.

While many manufacturers/distributors list single fiber availability (usually in some form of protective sheath), only a few manufacturers provide fiber bundles - and these are usually of discrete length (whereas single fibers are generally available in extended lengths, up to one kilometer). Since most of the available fibers (or bundles) are currently produced for the communications industry, fibers for use in aircraft fire detection systems would have to be specifically procured, probably at the bare clad-core stage, and special sheathing produced which incorporates physical strengthening (e.g. against rough handling, vibration, and minimum bending radii). Although the cost of producing such aircraft-qualified fiber "cables" could not be estimated by manufacturers at this time, it is expected that such cables (in mass production) could be made available at from \$0.80 per meter to just over \$3.00 per meter, depending on manufacturer. Fiber costs are significantly more dependent on the length of fiber than on the diameter of the fiber. Also it should be noted that non-UV (i.e. plastic) fibers for visible light transmission have come down in price over the past few years from several dollars per meter to just a few cents per meter. Costs as low as \$.06 per foot (\$.18 per meter) are currently being quoted for such fibers and, as usual, are elastic in price with the demand for quantity production<sup>9/</sup>.

No current supplier or manufacturer of optical fibers could present valid evaluation data on vibration/shock survivability of such fibers\*, although most indicated a belief that if fiber cables were properly tied down (not allowed to swing free over long spans) such cables would probably be no more susceptible to damage than would equivalent sized electrical cables. This is probably true in view of the low unit-length weight of optical fibers (approximately 10% of the weight of an equivalent cross-sectional size electrical wire). The minimum bend radius for most fibers is about 10 to 20 times

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\* A recent Army-sponsored study<sup>9/</sup> of communications fibers indicated that Suprasil 1 and 2 fibers of .085" core diameter met MIL-STD-202 standards for military conditions without damage.

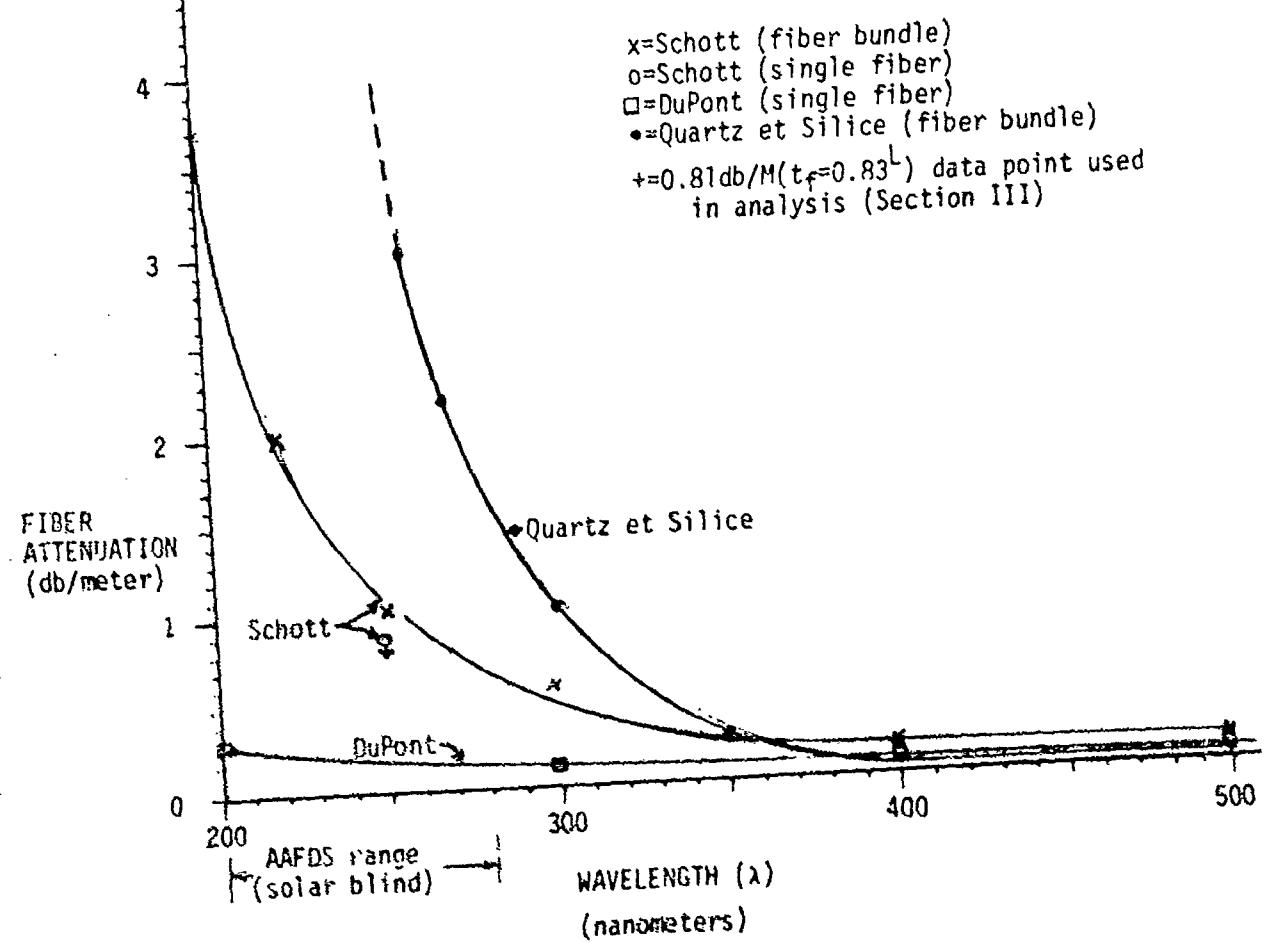
TABLE 2: MANUFACTURERS DATA ON AVAILABLE UV OPTIC FIBERS

Manufacturer/Supplier	Temp. * Rating (°C)	Materials		Dimensions*		Min. Bend Radius* (in.)	Attenuation (db/Meter @ 250nm)	N.A. or θ <sub>NA</sub> <sup>3/</sup>	Cost (\$/M)	Remarks
		Core	Cladding	Diameter	Length					
Quartz Products (Plainfield, N.J.) Rep: Quartz et Silice	250	Quartz	Silicone	.008" to .04"	33 ft to 10,000ft	.04 to 0.	4-6	.22	\$1.5 to \$25	Only large dia- meter fiber source. Teflon jacketed.
Welch Allyn (Skaneateles Falls, Rep: Schott	240	Quartz	Silicone	.003" to .004"	5 ft.	2" / 1	4	10 <sup>0</sup> 150	\$181 <sup>1/</sup>	basic fiber availability from Schott unknown
Galileo (Sturbridge, Mass)	240+	Quartz	SiO <sub>2</sub>	.004" to .008"	"un- limited"	n/a	n/a	n/a	\$9 <sup>2/</sup>	Bundles only available
DuPont (Wilmington, Del.)	250	Quartz	SiO <sub>2</sub> resin	.008"	"1000's of ft."	n/a	0.20	.22	\$2.25	Aramid sheath (lot temp. mat'l)
Corning Glass (Corning, N.Y.)	235	Quartz	Acetate	0.0003" to 0.002"	n/a	n/a	(no data in UV region)			
Valtec (Boston, MA)	204	Quartz	Silicone	0.01"	3300 ft.	1"	n/a	n/a	\$2	No UV data available
Fort	n/a	Silica	n/a	0.005"	5000 ft.	n/a	n/a	18-20	n/a	No UV data available

KEY: \* = core and cladding only (unless otherwise noted)  
n/a = data not available from manufacturer or supplier

NOTES: 1/ in bundles with armored sheathing on cable  
2/ 19 fiber (.004" dia. fiber) bundle only  
3/ θ<sub>NA</sub> = sin<sup>-1</sup> N.A. = half angle of acceptance

Figure 1 : UV ATTENUATION OF COMMERCIAL FIBERS



the nominal diameter of the clad fiber core; with recommended bend radius approaching 40 core diameters if transmission losses are to be minimized. Manufacturers' data (and several recent papers) suggest that losses up to 7dB per bend of less than 20 fiber core diameters can be expected, with such losses falling off to below 1dB per 40xdiameter bends.

In general, then, UV conducting optical fibers are currently available in quantity, in useful diameters and extensive lengths, and at prices reasonable enough to be seriously considered for aircraft fire detection system applications. While presently available cladding materials may limit their use in aircraft environments below 240°C (unless suitably sheathed and heat sunked), these fibers should be adequate for concept development and system prototyping (if not production) purposes. Further development of magnesium fluoride and other possible (but unexplored)\* clad quartz fibers, if given the proper incentives for their applicability and use, could conceivably provide a long term solution to very high temperature aircraft fire detection system needs.

### 2.3 OTHER OPTICAL SYSTEM COMPONENTS

Although fibers suitable for optically coupled AAFDS evaluations were of prime concern in this study, such a study would not be complete without a review of the other components necessary in making such a subsystem work. Fortunately, these other components (with one notable exception) are at an advanced state-of-the-art far beyond those of the UV fibers themselves. The following paragraphs review each category of other essential elements of an optically coupled fire detection system:

1. UV Optics - Since ultraviolet has long been the subject of both laboratory-level study and, more recently, of space and scientific and industrial applications (including photography), optics for UV application in the form of lenses, mirrors, filters, etc. are readily available from a number of manufacturers (Melles Griot, Special Optics, Inc., Acton Research Corporation, Ditric Optics, etc.), although standardly stocked optics tend to be of slightly larger size than the minimum sizes potentially required

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\* the possible applicability of sapphire and other "exotic" fibers was briefly reviewed in the course of this study, but were quickly rejected due to their general lack of development, potential cost and diameter/length limitations.



for aircraft fire detection systems. Several manufacturers of "micro-optics" were contacted by telephone late in this study (when the size of optics required became apparent), but were not able to send specific data on UV micro-optics in time to be included for consideration herein. However, these manufacturers alleged that they saw "...no problem..." in manufacturing non-precision quartz (probably Suprasil 1 or equivalent quality) optics in the range of diameters, focal lengths and types required for aircraft fire detection system applications. Their chief concern was in forecasting the cost of such UV micro-optics since little or no experience has been acquired to date. While low production volume, ultra-high quality precision macro-optics for UV tend to cost, at present, in the neighborhood of \$50 per lens element, a general trend toward costs in the \$5-to-\$10 per element for large production run, non-precision\* Suprasil 1 optics can be envisioned. One question that might arise in the application of such optics is the dimensional tolerances that need be held. Although optical imperfections (e.g. bubbles) are not important, focal lengths are. However, much of any possible dimensional tolerance problems can be compensated for (in system production) by optical adjustment and by the fact that only paraxial rays will be of interest.

Optical coatings for use in the ultraviolet to reduce lens reflections and/or to act as UV band pass filters are widespread in the current state-of-the-art. Ultraviolet-enhanced aluminum coatings (aluminum clad with  $MgF_2$ ) for mirrors, offering over 88% reflectance in the 180-400nm range are in standard use and production. Wherever possible, in fact, mirror (reflecting) elements should be used in preference to lenses (refracting elements) due to both their higher transmission coefficient and lighter weight, as well as lower costs involved.\*\* Antireflective coatings (the same  $MgF_2$  of interest in fiber cladding) as well as partially reflective coatings (for partial mirrors and similar beam-coating elements) are also available at nominal cost in production quantities. Such coatings can also be applied to lenses, mirrors, and other optical elements to provide band-pass (UV) filtering of undesired

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\* since UV optics for fire detection systems are primarily "energy collectors", and not precision imaging elements, the high degree of precision found in laboratory or photographic UV optics is not required.

\*\* for example, a 30mm diameter precision concave spherical mirror for UV costs \$17 compared to a 5mm lens at \$67 - both from the same manufacturer.

visible wavelengths to prevent these "noise" elements from reaching the UV detectors.

2. Optical Couplers: While optical couplers for fan-in and fan-out (single fiber to bundle and bundle to single fiber) are available for visible wavelength applications (from Galileo Electro-Optics Corp. and others), no reference was found for such items in the manufacturers literature - nor, for that matter in our literature search - as being applicable to UV wavelengths. This is probably due to the extreme difficulty in obtaining the precise alignment of fiber ends at such short wavelengths. The literature for visible wavelengths notes dimensional tolerances on the order of  $\pm 3$  micrometer ( $10^{-4}$  inch) for such couplers. Although coupling elements would be of value in designing UV fiber-optically coupled fire detection systems to reduce multiple sensor fiber runs to a single fiber, they are not deemed critical elements of such designs. In fact, the desire to run a second parallel, small diameter fiber to provide a UV test signal to each sensor head would tend to obviate the desirability for using couplers in AAFDS designs.

3. Connectors, etc: Interconnecting elements for fiber optic cables are generally available at low cost from such manufacturers as Amphenol, AMP, Inc., Fibre Link, Belden, etc. Many of these products use MIL-C-39012 SMA qualified components meeting all MIL-STD-202 environmental requirements for shock, vibration, corrosion, etc. While these connectors are rated for a temperature range of only  $-55^{\circ}\text{C}$  to  $+199^{\circ}\text{C}$  at the present time, this limit is believed to be primarily due to the fiber cable-to-connector bonding methods used, rather than as an inherent thermal limit of the (metal) connectors themselves. Both single fiber cable and bundle connectors (for up to 6 or more fibers) are currently in production and are available at prices comparable to equivalent electrical connectors.

Thus, with the possible exception of optical fiber coupling devices for fan-in/fan-out usage (probably not a required element of aircraft fire detection systems using fiber optics), all of the critical elements are either in widespread production or in an advanced state-of-the-art necessary to begin serious consideration of designing (and building) an optically coupled UV AAFDS. Such system considerations are the subject of the next section of this report.

## SECTION III

### OPTICALLY COUPLED FIRE DETECTION SYSTEMS

#### 3.1 GENERAL SYSTEMS CONSIDERATIONS

Two current problems in UV fire detection aboard aircraft make optically coupled systems particularly attractive.

1. The many void spaces in aircraft where fires could occur necessitates either a large number of UV sensor head locations or exceptionally sensitive flame detectors which are able to "see around" the obstacles which normally block UV radiation transmission in their vicinity (e.g. smoke, fumes, intervening equipment, etc.). But...
2. "Bare detector" systems are relatively expensive, weighty, voluminous, and of low quantum efficiency to permit a large number of sensing points. And they are relatively sensitive to high ambient temperatures encountered in most aircraft installations (e.g. around engines).

If optically coupled systems can be designed which overcome either or both of these problems inherent in present "bare detector" systems, then several potential advantages can be realized:

1. A greater number of fire surveillance spaces can be monitored with a very little penalty (relative to "bare detector" systems) in weight, volume and - hopefully - cost, thus providing more efficient, effective, and complete fire surveillance.
2. The self-generated attenuators of fire-radiated UV (smoke, vapors, etc.) will have less effect on short-range detection systems viz a viz long-range detector systems.
3. Optical coupling could permit the removal of UV detectors themselves to lower ambient temperature regions where increased sensitivity to fire-generated UV radiation, and lower "false alarm" rates can be attained.

With such goals in mind, several types of optically coupled UV fire detection

systems were conceived and analyzed in the course of this study. But before proceeding to the analysis, let us first review the application considerations of interest.

### Aircraft Fire Detection System Requirements

With a few notable exceptions, the overall problem of fire detection in aircraft is one of providing surveillance coverage in a large number of relatively small, isolated volumetric spaces. The opportunity for "long range" (distance from UV sensor to fire location) surveillance is limited primarily to a few wing and fuselage areas where fuel and hydraulic line passages may be better characterized as tubular or conical in shape, rather than the more prevalent small rectangular or spherical volume.

In a typical engine installation, for example, whether the engine is housed outboard in an external nacelle (e.g. C-141, KC-135, etc.) or inboard in the main fuselage or flared housings (e.g. F/B-111, F-104), the spaces in which fires are most likely to occur are within an annulus surrounding the engine and within the confines of the nacelle or airframe. While such annular areas are characteristically "long" (compared to the thickness of the annulus radially), they are quite compartmented or otherwise broken up by bulkheads and equipments (e.g. fuel pumps, fuel feed lines, manifolds). As a result, even such "annular" spaces are (insofar as UV radiation transmission paths are concerned) relatively small annular segments approximating "cubes" of finite size (probably averaging 1 to 3 cubic feet in total volume).

Figures 2 and 3 illustrate a typical jet engine installation in a nacelle assembly. Note the apparent absence of clear optical paths axially through the annulus formed by the outside of the engine (and its attached auxiliary equipments) and the inside of the engine nacelle housing (shown in Figure 3 removed for exterior view access, but easily visualized in its in-place position by noting the adjacent closed nacelle housing areas to the left and right of the exposed area).

Although the Air Force specification for testing aircraft fire detection systems (MIL-D-27729A) calls for a fire detectivity "...range of 4 feet from a MIL-STD 5 inch pan fire..." in a free field environment (for detector qualification testing), it is quite obvious that such conditions are infrequently encountered in real practice in aircraft fire surveillance

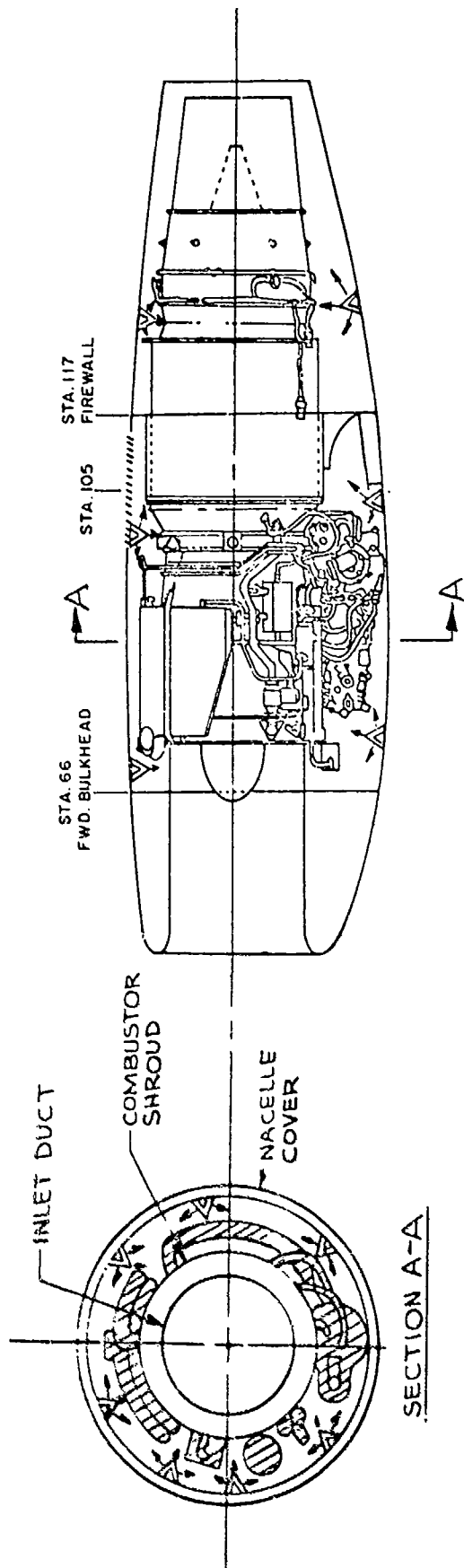
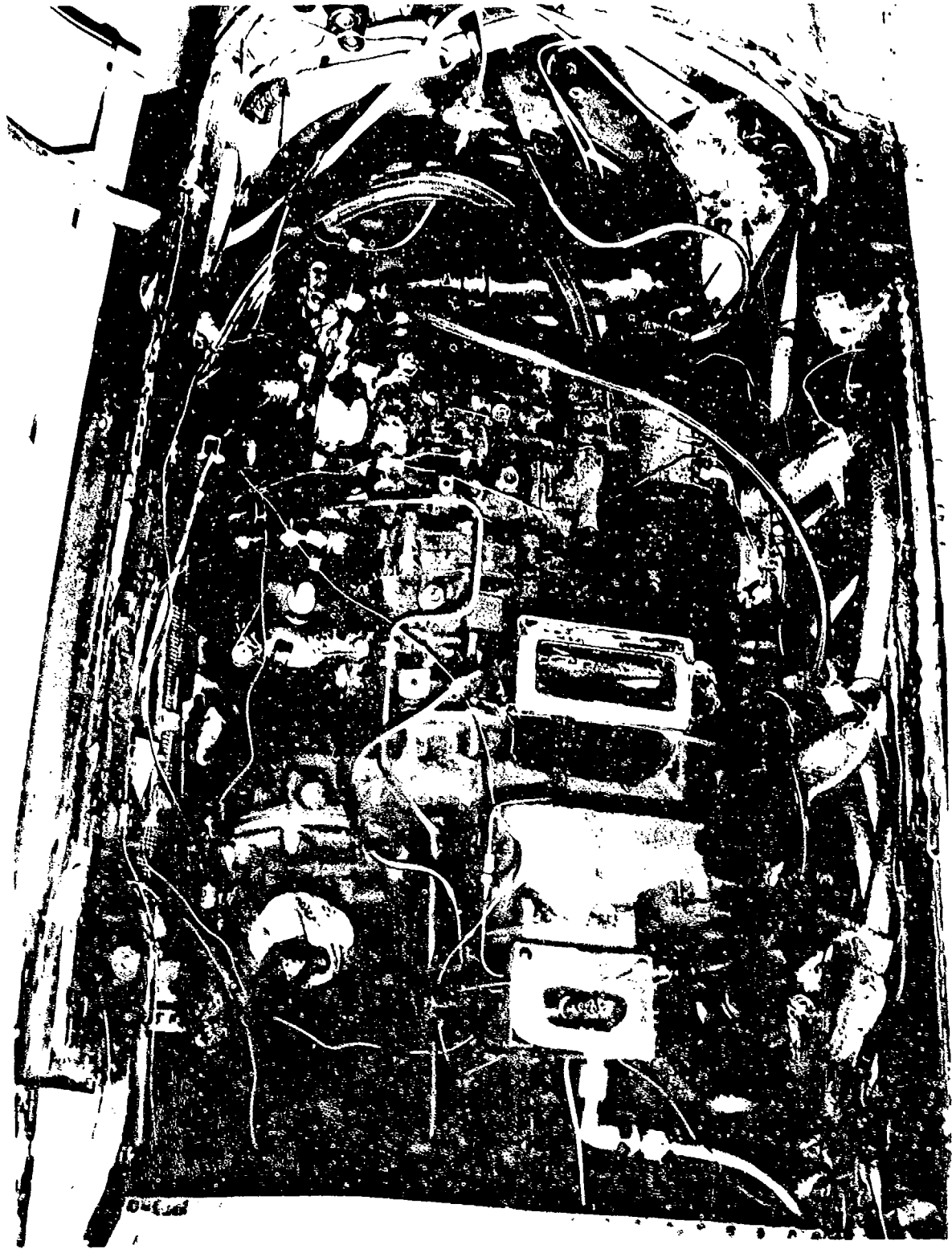


FIGURE 2: TYPICAL JET ENGINE INSTALLATION  
(C-140/J-12 power plant)



(C-140/J-12 6 o'clock, nacelle open, station 105)

FIGURE 3: TYPICAL ENGINE INSTALLATION WITH UV "BARE DETECTORS" INSTALLED

(other than, perhaps, in empty cargo void spaces, etc.). Of course, real aircraft fires - it may be argued - are not characteristically "...MIL STD 5 inch pan fires..." either. Yet how do "bare detector" UV fire detection systems which have met the MIL-D-27729A qualification criteria perform in "real world" aircraft (engine) fire testing?

In 1974, the Federal Aviation Administration reported on a series of fire detection system tests employing a C-140 powerplant (J-12 engine) installation with two types of "bare bulb" detection systems installed.<sup>5/</sup> Four "bare bulb" detector heads of each of two manufacturers' types were installed on oppositely facing bulkheads some 51 inches apart, with the detector heads arranged to "see" along the long axis of the annulus. Each "bare detector" head then could cover (in theory) approximately one quadrant of the annulus formed between the engine and its surrounding nacelle structure. Regulated fuel-flow fire injectors were located at points between the two fire detection systems' mounting bulkheads (thus providing less than 4 foot separation between any given fire injection point and a fire detector head). Test fires were initiated using JP-4 fuel flow rates of anywhere from 10 to 32 times the "MIL STD 5 inch pan fire" combustion rates. The results were interesting.

While both detector systems were able to detect the highest fuel-feed-rate fires that were within direct view of one or more detector heads (i.e. illuminated by direct UV radiation on the order of 200 times the luminous flux intensity, measured at the detector head, of the "MIL STD 5 inch pan fire"), the high level (high fuel rate fed) fires that were obscured from view by the "bare bulb" UV detector heads were not detected. On the other hand, the low-level fires (still approximately 80 times the UV luminous flux intensity measured at the detector heads of the "MIL STD 5 inch pan fire") went undetected in several cases, even when the fires were within the direct view of a detector head (but were possibly obscured by smoke or fumes).\*

This is not to criticize either the Air Force's MIL-D-27729A qualification criteria for aircraft fire detection systems, nor the two

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\*in a similar test series conducted for the Air Force in 1971 on a C-140 J-12 power plant operated at simulated flight conditions, only 3 of 14 fires (averaging from 50 to 150 times the luminous intensity of the "MIL STD 5 inch pan fire) were detected<sup>4/</sup>.

manufacturers' UV fire detection systems that were tested. It is merely to point out the extreme difficulty of practical UV fire detection which relies on the detection of UV radiation over long, and obscured distances. What such test results show is that highly distributed fire detection systems are required to reliably warn aircrews against fires and, at the same time, reduce the probability of false alarms resulting from "pressed-to-the-limit-of-sensitivity", high ambient temperature "bare bulb" detector systems.

In the design of UV fire detection systems for aircraft, then, one should concern themselves more with "volumetric" coverage (wide angle, short detection range) systems. How far the UV fire detection sensors can "see" (i.e. detect a fire) is not nearly so important in such cases as how much they can "see" at short range. Fortunately, this characteristic offers the UV fire detection system designer a convenient tradeoff in his consideration of the UV photometric equivalents. He can give up narrow angles of detector acceptance necessary to "reach out" great distances, since radiation attenuates according to the inverse square law (luminosity decreasing with the inverse square of the distance,  $1/d^2$ ), for wider angles of surveillance (a doubling of the view angle obeying a similar squaring law,  $1/a^2$ ). For very short distances such as the maximum dimension of the void areas encountered in aircraft which require fire surveillance, an essentially hemispherical lens or mirror system can be used to collect UV emissions sufficient to trigger a UV detector tube.

If one thinks of each fiber optically coupled distributed sensor head (DSH) as an "eyeball" having a hemispherical field of view, the fire surveillance system then becomes one of positioning a number of such DSHs around, say, the annulus of an engine nacelle, in such a manner that each DSH covers a hemispherical volume that slightly overlaps the adjacent DSH's field of view (Figure 4). The question then becomes, just how many such wide-angle, short detection range DSH "eyeballs" are necessary to cover the areas of aircraft fire surveillance interest?

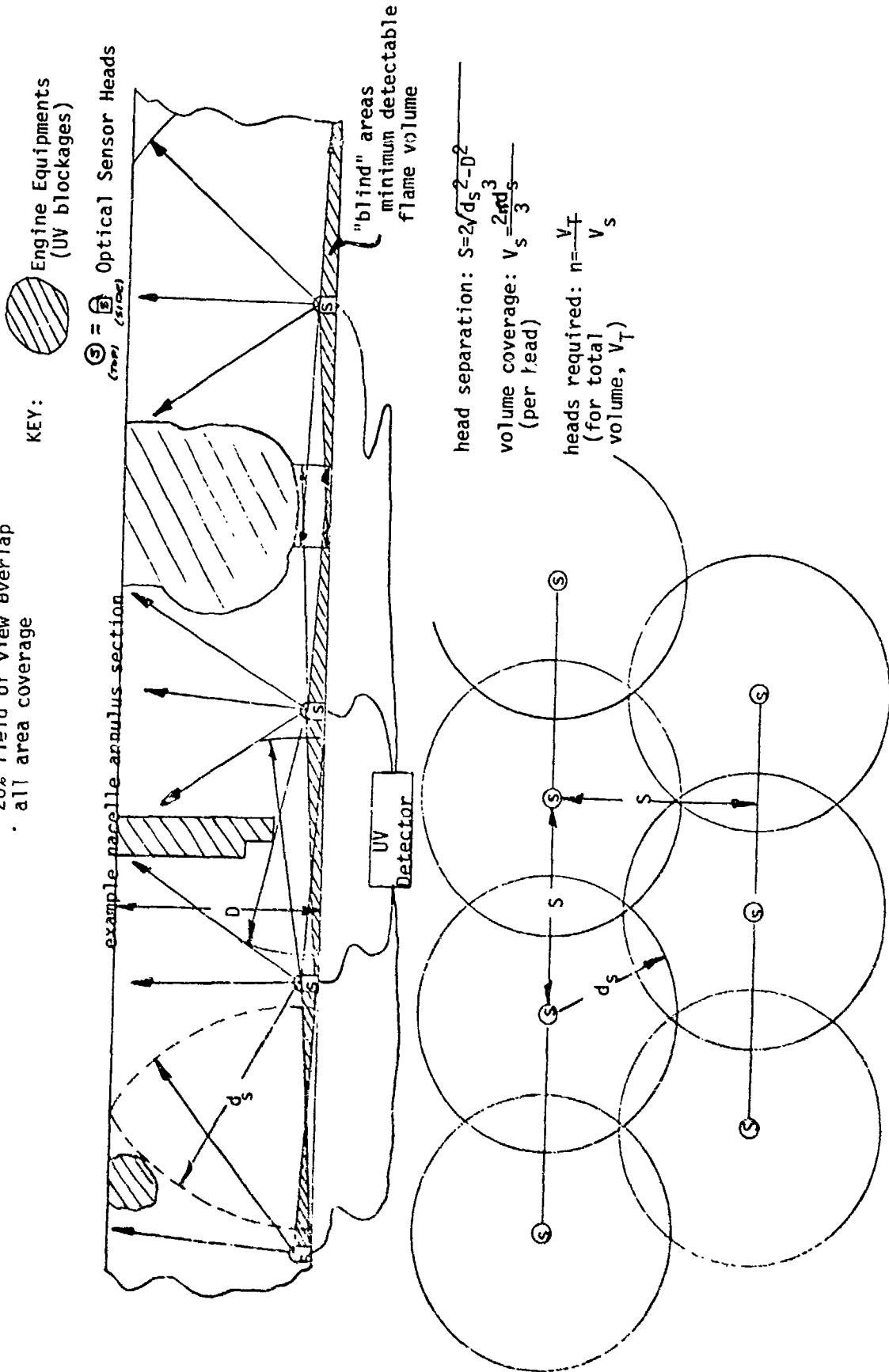
Taking the C-140 powerplant nacelle (housing one J-12 engine) as an example, and making a few simplifying assumptions and approximations, we estimated the total fire surveillance void volume presented inside each such nacelle/engine annulus as follows:

- assuming the area of fire surveillance to be that region between station 66 (forward bulkhead) and station 117 (firewall)-



FIGURE 4: DISTRIBUTED SENSOR SYSTEM CONCEPT

- 20% field of view overlap
- all area coverage



see Figure 2 - a length of annulus of 117-66 = 51 inches, and assuming the diameter of the J-12 engine as approximately 25 inches and that of the nacelle as 36 inches (values scaled from Figure 2), the total annular "void" volume of interest is

$$V_a = V_n - V_e = \pi L (r_n^2 - r_e^2) = 15.6 \text{ ft}^3$$

Even if the entire annular volume of nearly 16 cubic feet were completely free space (which it isn't...probably less than 40% of it is not occupied by major equipments of some considerable volume, judging from Figure 3), a system of only 7 DSHs, each having a semi-hemispheric volume coverage of  $3.5 \text{ ft}^3$  (an effective range of only 18 inches per DSH) would provide complete coverage with an overlap of 50% (each DSH seeing one half the surveillance volume of the adjacent DSH) placed only at the ends of the annulus.

With such an arrangement, a "MIL STD 5 inch pan fire" could be detected anywhere within the C-140 engine/nacelle annulus with a significantly higher probability than that of "bare detector" systems involving from 3 to 8 detector heads.

### 3.3 CONCEPTUAL FIBER OPTIC COUPLED SYSTEMS

Fiber optic coupled aircraft fire detection systems intrinsically have the desired characteristics of being able to both expand the number of areas monitored by one (or a few) UV detectors and to more efficiently couple the UV radiation from flames back to radiation detectors located in lower temperature ambient environments. Since we know that certain (albeit limited) fiber optics and components for UV exist in the current state-of-the-art, the question then becomes how (or if) they can be used to build a workable AAFDS; and how effective would such an optically coupled system be?

As previously noted, two basic types of fiber optically coupled systems appear to be of interest: highly distributed systems (where many optical sensor heads are distributed throughout the aircraft's small void spaces, and where each such head needs to "see" only a short distance), and improved optically coupled "long look" systems (which maintain or increase the view distance of "bare bulb" detectors by more efficiently coupling the fire-emitted UV radiation into the UV detector itself).

Each of these two basic types were investigated and analyzed to ascertain their payoffs and limitations in terms of performance, reliability, cost, weight and volume viz a viz the "bare detector" baseline systems presently under development.

### Distributed Systems

Figure 5 depicts a conceptual fiber optic coupled system of the distributed type. The principle elements of such a system are:

1. A number of sensor heads with input optics to couple UV energy to the fiber.
2. An optical fiber (or fiber bundle) interconnecting the sensor head to the detector transfer optics.
3. A set of detector transfer optics coupling a number of fiber transmission lines to the UV detector.

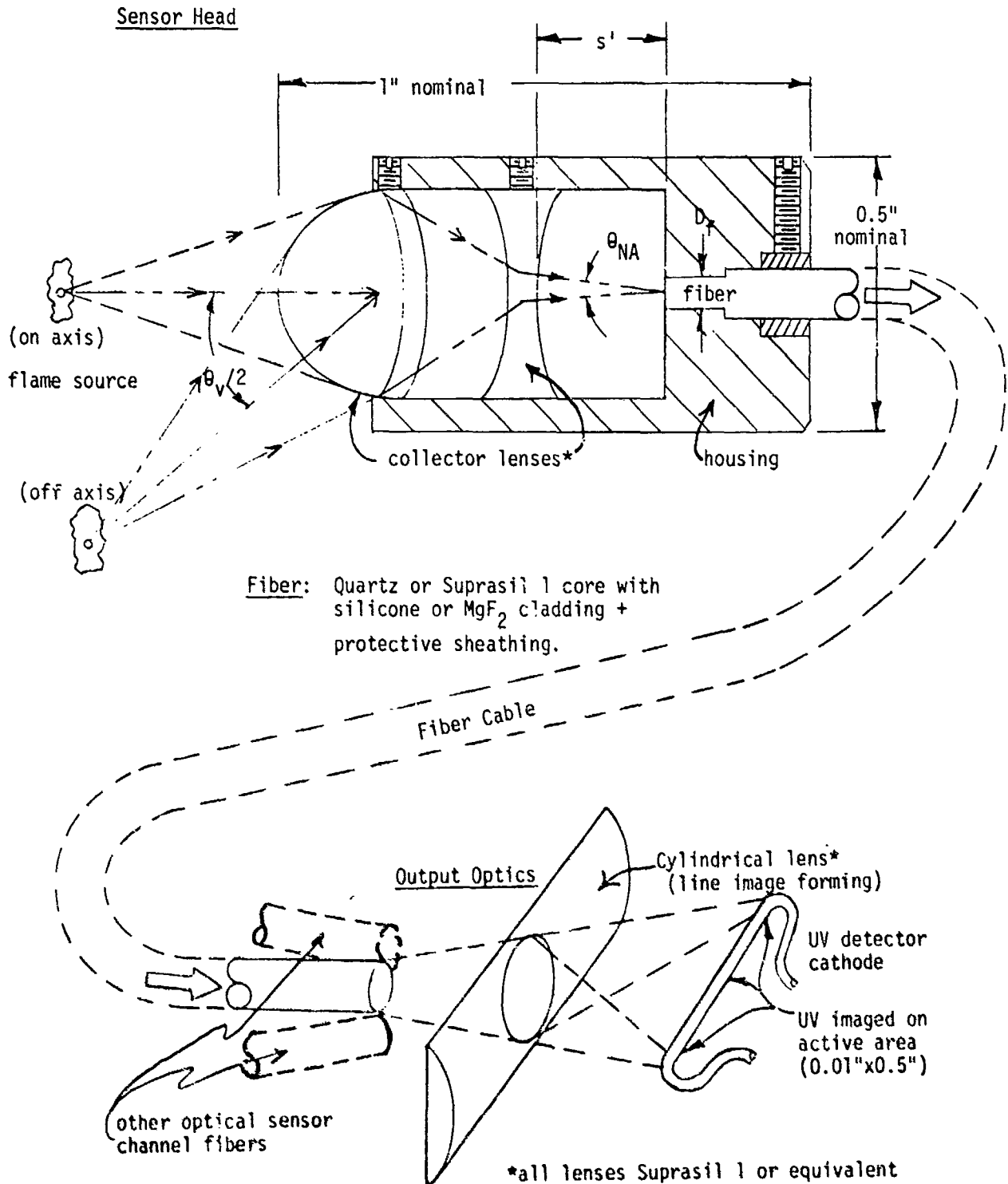
A large number of sensor heads may be employed, each of which has a wide view angle but a short view range. Each of these sensor heads is connected through an optical fiber (or bundle of fibers) back to the UV detector (which may now be located in a lower temperature ambient environment for increased sensitivity to UV radiation with a reduced danger of "false alarms" generated through thermal and other non-flame generated effects). Since each of the distributed sensor heads optically couples flame-generated UV radiation from only a limited surveillance volume (perhaps on the order of a few cubic feet or less), many such sensor heads would be coupled into a single detector tube (assuming that precise location of the fire source is not a desirable additional feature of such systems, but merely that the presence of a fire in a region of many such sensor heads is all the information that is required).

While the fire detection range of each sensor head of the distributed system is low, a fire may be detected through any one or more sensor head/fiber-coupled channels with quite efficient optical coupling at the detector tube end of the chain. In concept, a fire (equivalent to the MIL STD 5 inch pan fire, as a comparison baseline) within the detection range of any sensor head would

FIGURE 5

FIBER OPTIC COUPLING SYSTEM CONCEPT FOR U.V. FIRE DETECTION

(not to scale)



provide sufficient UV radiation in the 200-280 nm wavelength region to trigger the UV detector system into an alarm indication. By positioning the sensor heads in spatial arrays such that the field and range of view of any one sensor head overlapped those of other sensor heads (Figure 4), fire coverage redundancy could be achieved. Additionally, a test UV source could be fiber optically "piped" to each sensor head and used to periodically test the validity of the system, much as is now done in existing "bare detector" fire detection system designs.

In concept, such distributive systems have the advantage that no potential fire of any appreciable magnitude (probably much smaller than the MIL STD 5 inch pan fire) would go undetected if all fire surveillance volumes were within range of at least one sensor head. The obvious "penalty" paid by such distributed systems is that a large number of sensor head/transmission fibers must be employed to cover the total surveillance volume. However, since each of the distributed sensor head/connecting fiber units could be made quite small, inexpensive, and light weight, the tradeoffs with "bare detector" systems should be of considerable interest.

The primary concern with such distributed systems would then become those of installation and maintenance. Would independently arrayed distributed sensor heads (DSH) present a greatly more difficult problem to install and maintain? If such DSH arrays were "fanned out" from fiber optic bundles of, say 10 to 20 channels (a channel representing one DSH and its associated optical fiber) to cover a total volume of, say, 8 to 16 cubic feet (assuming a 50% overlap of DSH view-fields for redundancy), it is believed that such systems would not be any more difficult to install and maintain than the "long look" systems described below. One concept for installing such distributed systems (in engine nacelle areas, for example) would be to communicate the fiber optic array bundle sets along the inner skin of the nacelle itself (a surface not presently used due to structural considerations, but little effected by the light weight and volume fiber optic DSH arrays). Such a configuration would present little impediment to maintenance crews, where the nacelle access panels hinge or fold back out of the way for maintenance access to begin with. Removable nacelle/aircraft skin panels could be fitted with fiber connectors if sufficiently close alignment can be achieved (for 1-on-1 fiber coupling, this should not be a significant

problem).

Distributed sensor arrays are of particular interest where the surveillance volume is characterized by shallow depths, away from the DSH mounting surface. For large volumes (such as cargo spaces), DSH type coupling would probably be less desirable than the "long look", large volume type systems.

#### "Long Look" Systems

The second important (albeit less frequently encountered) type UV fire detection system for potential fiber optic consideration is that type characterized by volumes which can be described as "long" or large in the dimension along the central viewing axis of the sensor head. Some examples of such volumes might be in confined areas (such as wings) where fuel lines run through confined "tubes", or more prevalently, in cargo and weapon stores areas aboard aircraft. The primary characteristic of such volumes is that there is usually no structural surface available for mounting the sensor that does not require the sensor to view potential fires at long range. Thus, "long look" sensors are needed to look across (or through) significantly long cones or tubes of detection, perhaps up to 8 or 10 feet or more in length, i.e. must "reach out" in their detectivity patterns. "Long look" (LL) systems trade off view angle (small) for detection range (large) compared to the large view angle and short detection range of DSH systems. The optics of LL systems, then, are different from DSH optics. To fill a large LL volume, many sensors (or some means of otherwise covering the entire surveillance volume of interest) may be required; in other applications, only a few long-look sensor heads (LLSH) may be needed.

One of the chief problems to be encountered by LL systems (and hence, a valid reason for applying them only where DSH - "short look" - sensors cannot be applied) is that of environmental attenuation in an aircraft fire sensing environment. Fires will usually be accompanied (or preceded) by the generation of smoke, vapors or other UV absorptive media which obstruct or totally obscure the UV radiation generated by the fire itself. Since such obscuration is a function of the distance through which the UV radiation must penetrate to the sensor head, LL systems require an absolute maximum sensitivity (i.e. absolutely minimum transmission losses within the

coupling optics system). With the assumption (for purposes of this study) of a standard "5 inch JP-4 pan fire" source and the McGraw-Edison MK II UV detection system as the input/output ends of the fiber optics interfacing sub-system, the "long look" concept must provide the maximum fire detection range possible while still compensating for the transmission losses between the sensor head and the UV detector. Optically, this indicates that each sensor head array (and its related optics) maximally couple the flame-size detection threshold (taken as the 5 inch pan fire) to the UV detector, with very limited losses in the optic system itself and possibly, a considerable increase in the sensitivity of the UV detector itself. While such detectivity increases may be achievable with the present family of gas discharge type detectors (having quantum efficiencies on the order of  $10^{-4}$  to  $10^{-5}$  photoelectrons or "counts" per UV photon), it seems likely that other types of "solar blind" UV detectors would be required for "long look" fire surveillance systems. While the investigation of such high-efficiency detectors was beyond the scope of the present study, it was noted that several types of UV detectors that would be compatible with the lower temperature environments made possible by optical coupling to remotely located detectors operating in a less severe environment do exist within the state of the art. For example, the RCA types C31005 and 70128 photomultipliers have "solar blind" spectral responses below 300 nm and offer greatly increased quantum efficiencies approaching 7% ( $7 \times 10^{-2}$ , or nearly 1,000 to 10,000 times as sensitive as the gas-discharge tube).

In both the "short-range", distributed sensor and "long look" concepts for optically coupled UV fire detection systems, multiple optical sensor heads are required. Just how many such optical heads can be coupled to a UV detector, and the allowable coupling (transmission) losses of such sensors is analyzed in the following sub-section. The tradeoffs of such optically coupled systems (cost, weight, volume) is covered in the last part of this section.

## Optically Coupled Fire Detection Systems

It can be shown (see Appendix B) that the detectivity gain for any optically coupled detection system, relative to that of an unaided (non-optically coupled) system, can be expressed by the relationship:

$$(1) \quad \frac{P(\lambda)_s}{P(\lambda)_b} = \left( \frac{A_s}{A_b} \right) \left( \frac{d_b}{d_s} \right)^2 T_s$$

where:  $P(\lambda)_s$  is the power coupled to the detector (at wavelength  $\lambda$ ) via the optical system at a distance  $d_s$ .

$P(\lambda)_b$  is the power coupled to a "bare detector" at a distance  $d_b$ .

$A_s$  is the effective aperture area of the optics system

$A_b$  is the effective sensitive area of the bare detector

$d_b$  is the bare detector to flame distance

$d_s$  is the optical system head (input optics) to flame distance

$T_s$  is the lumped transmission coefficient of the optical system

That is, the optical gain over a "bare detector" system  $\left( \frac{A_s}{A_b} \right)$  is a direct function of the optics employed, and can be made much greater than one to enhance the detectivity over that of any "bare detector" alone. The net system gain is then the excess of optical gain over the optical transmission losses  $\left( \frac{A_s T_s}{A_b} \right)$ .

For purposes of our analysis we chose to take a "baseline" system familiar to those in the UV fire detection field and compare what optically coupled systems could do to enhance the performance (detectivity) and reduce the cost, weight, and size of such "bare detector"-only systems. For this baseline, we chose the McGraw-Edison fire detection system using the MK II (Edison 42743-8HTL) gas discharge UV detector tube (active area = 0.005 inches<sup>2</sup>) with its associated electronics. The Edison "bare detector" system produces approximately 50 "counts" per second in response to a MIL-D-27729A standard 5 inch JP-4 pan fire at a distance of 4.0 feet (in free space). Taking this "count rate" (tube avalanches in response to UV radiation) as the threshold detection level that produces a "FIRE" indication response by the Edison system, equation (1) may be rewritten:

$$(2) \quad \frac{C_s}{50} = \left( \frac{A_s}{.005} \right) \left( \frac{d_b}{d_s} \right)^2 T_s$$



$$\text{or } C_s = 1.60 \times 10^5 \frac{A_s T_s}{d_s^2} \text{ counts per second}$$

when  $A_s$  is in inches<sup>2</sup>  
 $d_s$  is in feet

Now, for comparative purposes, we can choose to set  $C_s = 50$  counts per second also (since this is the Edison fire detection system count threshold necessary and sufficient to give a "FIRE" warning indication), i.e. to select a required overall system "gain" = 1. We can then obtain a working parametric equation to explore the optical system tradeoffs and/or to design an optical system. The parametric optically-coupled system equation then becomes:

$$(3) \quad d_s^2 = 3.2 \times 10^3 A_s T_s$$

Next, we can evaluate the lumped transmission coefficient,  $T_s$ . For a wide range of optical systems that could be employed, each such system can be considered as composed of three separate sub-system groups:

1. A number of optical sensor "heads" or UV radiation collection sub-systems.
2. An optical fiber (or fiber bundle) transmission cable sub-system.
3. An optical coupling system to transfer the UV "information" from the fiber(s) transmission lines to the UV detector tube.

Such a generalized system is shown in Figure 5. Note that a large number of transmission lines (fibers) may be coupled into a single detector tube, thus providing an "area of coverage" multiplier of considerable importance in aircraft fire detection systems applications. This factor is not included in the optical sub-system design evaluation equation being explored in this sub-section, since we will look first at a single channel of such a system. As such, the parametric design equation (3) need be solved only for each sensor head/transmission line set to be coupled into the detector with the detector-coupling optics being the same for all sensor channels coupled to a single detector tube. Here, the detector coupling optics are treated as the third lens of a typical channel.

The lumped optical system transmission coefficient ( $T_s$ ) consists of two elements at most (and possibly only one), i.e.:

$$T_s = t_n t_f$$

where  $t_n$  is the lens and/or mirror transmission coefficients

$t_f$  is the fiber transmission coefficient

For a wide variety of UV optical coupling systems, these transmission coefficients may be evaluated as:

$t_n = .90^n$  where  $n$  is the number of lenses or mirrors\* employed

$t_f = .87 \times .83^L P_f$  where  $L$  is the fiber transmission length (in meters) and  $P_f$  is the fiber bundle packing fraction ( $P_f = 1$  for a single fiber)\*\*

Thus a generalized equation for optically coupled systems may be written as:

$$(4) \quad d_s^2 = 2.784 \times 10^3 A_s (.9)^N (.83)^L P_f$$

If equation (4) is rewritten in terms of the effective (input) optics aperture diameter ( $D_{eff}$ ) then,

$$(5) \quad D_{eff} = \left[ \frac{d_s^2}{2.187 \times 10^3 (.9)^N (.83)^L P_f} \right]^{1/2} \quad \text{since}^{***} \quad A_{eff} = \frac{\pi D_{eff}^2}{4}$$

Where  $d_s$  is in feet

$D_{eff}$  is in inches

$L$  is in meters

Note that the generalized optical system equation (5) is independent of both the field of view ( $\theta_v$ ) of the sensor head, and the fiber (or fiber bundle) diameter ( $D_f$ ). For most practical applications, i.e. for relatively simple

\* for all practical purposes, the reflection coefficients of ultra-violet-enhanced aluminum/MgF<sub>2</sub> coated mirrors and the transmission coefficients of Suprasil 1 lenses for the 200-280nm wavelength region are equal to about 90%.

\*\* although manufacturers data varies widely (probably due to different methods of measurement or calculation), a fairly consistent set of data shows a transmission coefficient of about .83<sup>L</sup>. The insertion/extraction losses average 13%, providing a one time multiplication factor of 0.87.

\*\*\* although circular cross section optics are assumed for simplification, any shaped optics, fibers, etc. may be applied by converting applicable areas to circular equivalent diameters.

optics, these parameters are related to the parameters contained in equation (5) as follows:

$$(6) \quad s' = \frac{D_{\text{eff}} - D_F}{2 \tan \theta_{\text{NA}}}$$

$$(7) \quad M = \frac{2 \tan^{-1} \left( \frac{D_F}{2s'} \right)}{\theta_V}$$

$$(8) \quad f_T = \frac{s' d_s}{s' + d_s}$$

where  $D_F$  is the fiber (or bundle) diameter (in inches)

$s'$  is the fiber-end to back lens distance (in inches)

$f_T$  is the aggregate focal length of the sensor head optics

$\theta_{\text{NA}}$  is the half angle of acceptance of the fiber(s) =  $\sin^{-1} \text{NA}$ ,  
where NA = the numerical aperture of the fiber(s)

$M$  is the magnification of the input (sensor head) optical system

Since the acceptance half-angle ( $\theta_{\text{NA}}$ ) of optical fibers is a property of the fibers themselves (ranging from  $8^\circ$  for fluorocarbon resin clad quartz fibers that are presently available, to  $26^\circ$  [theoretical value] for  $\text{MgF}_2$  clad quartz fibers which could be attainable in the future), and  $s'$  and  $M$  are optical system design parameters which can be controlled in the optical (sensor head) design, it is obvious that the effective aperture ( $D_{\text{eff}}$ ) and field of view ( $\theta_V$ ) can, within reasonable limits, be anything we want to make them in order to meet the assumed design criterion of the optical system's net gain being equal to unity.

Using equations (5), (6) and (7), one can "design" optically coupled fire detection systems using the following generalized procedures:

STEP 1: From general considerations of the aircraft areas to which fire detection is to be provided, determine the effective range ( $d_s$ ) and field of view ( $\theta_V$ ) of the type of optical sensor head required, and the length of fiber transmission line ( $L$ ) to be used.

STEP 2: Use equation (5) to determine the  $D_{\text{eff}}$  required, assuming (for the moment) "nominal" optics (usually 2 or 3 lenses and/or mirrors), and a single, large diameter fiber, i.e.  $P_f=1$ .

STEP 3: Design the input optical system (from requirements for  $D_{eff}$  from equation (5), determine  $D_F$ ,  $s'$ , and  $M$  from equation (6) and (7) as required).

STEP 4: If the active fiber diameter ( $D_F$ ) required is greater than that available in a single fiber (0.040 inch at present), recompute  $D_{eff}$  (using equation 5) for a  $P_f=.7$  (for plastic clad fibers) or  $P_f=.85$  for  $MgF_2$  clad fibers (or use other suitable  $P_f$  values as new fibers become available). Repeat steps 2 and 3, as required, to arrive at the "optimal" design.

Before proceeding with the analysis of several conceptual designs in the sections below, let us first consider the general effects of the potential improvements in optical fibers as indicated in Section II of this report.

From equations (5), (6) and (7), it may be seen that the increase in acceptance angle ( $\theta_{NA}$ ) offered by  $MgF_2$  or other similar thin-clad (and, fortuitously, high temperature) fibers has a "double" payoff in permitting both larger  $D_{eff}$  at shorter  $s'$  (optics-to-fiber coupling distance and, hence, reduced physical size, weight and probable cost of sensor head optics) while, at the same time, permitting the use of smaller fibers (or smaller bundles) for a given desired field of view ( $\theta_v$ ) or for a given optical magnification. While currently available plastic-clad fibers of low  $\theta_{NA}$  and  $D_F$  would tend to be critical factors in the development of practical optically coupled systems from the standpoint of attainable optical magnifications (on the order of .01 to .001), fiber bundle diameters, relatively low packing fractions and long optical coupling dimensions ( $s'$ ), the primary influence of both existing and new fiber developments will be in attaining reduced system cost. In today's state-of-the-art fiber market, fibers tend to cost "by the unit length" rather than as a function of fiber diameter. Thus, for a given length of transmission line (per sensor head or, when multiplied by the number of sensor heads per UV detector and thence per aircraft), the overall cost savings of large  $D_F$  and  $\theta_{NA}$  fibers could represent a considerable savings in the system. But many of the "shortcomings" of present fibers can be compensated by increasing the sensitivity (detectivity) of the UV detectors themselves or by simply in-

creasing the optical gain of each sensor head.\*

In the sections below, nominal design concepts are presented for both wide-angle, short-range "distributed" fire detection systems as well as for surveillance-volume-tailored "long-look" systems. In each case, the reader can determine the potential contributions the development of high-temperature, wide acceptance angle (high numerical aperture) fibers would make by solving equations (5), (6), and (7) using the appropriate new-fiber parameters ( $D_F$ ,  $t_F$ ,  $\theta_{NA}$ ).

#### Conceptual Systems

As previously noted, two basic types of optically coupled UV fire detection systems are required for aircraft: the "distributed" or short-range/wide-view angle type for areas such as engine nacelles where potential fire-surveillance areas are characterized by numerous small volumes; and "long-look" systems where surveillance volumes are characterized by larger detection distances (and narrower view angles). While, in principle, both of these type systems are similar from an optical viewpoint - each requiring a differently tailored optical sensor head, a fiber transmission line, and identical UV detector tube coupling elements - the primary difference lies in the design of the sensor head optics (assuming the same or similar transmission line length to a remote UV detector). The only differences in the transmission lines and hence in the UV detector coupling optics is the number of fiber channels that must be carried over the transmission line length (and hence, the cost of such systems may vary greatly since cost is highly correlated to fiber lengths). For the purposes of this study, however, we will assume that transmission line lengths for both type systems are equivalent, and that they will use the minimum number of fibers consistent with optical needs, system reliability, and cost/weight/volume considerations.

#### Distributed Systems

Figure 5 depicts a typical (conceptual) distributive system using a number of remotely located optical sensor heads and their associated optical fiber transmission lines coupled with one (or more) UV detectors of the gas-

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\* an optimized aircraft fire detection system should take advantage of improvements in both optical fibers and UV detectors to provide expanded fire detection surveillance and reduce system cost, size and weight.

discharge tube type. A number of possible sensor head optical systems are shown (conceptually) in Figure 6. While only one of these optical sensor head concepts could be analyzed within the scope of this study, each type offers certain characteristics of potential interest in further development of optically coupled systems (see Section IV).

Using equations (5), (6) and (7) the following analysis was made of a "typical" distributed (wide-angle, short-range of detection) system concept.

Let the design parameters be:

$$L = 5 \text{ meters}$$

$$d_s = 2.0 \text{ feet}$$

$$\theta_v = 150^\circ \text{ (vertical x } 360^\circ \text{ annular)}$$

Using current state-of-the-art fibers ( $NA = .139$  or  $\theta_{NA} = 8^\circ$ ,  $t_F = .83^L$ ,  $D_F \leq 0.040$  inch) and assuming the optical system to consist of 3 lenses and/or mirrors \* ( $N=3$ ), we can find the  $D_{eff}$  required from equation (5):

$$D_{eff} = \left( \frac{2^2}{2.187 \times 10^3 (.9)^3 (.83)^5} \right)^{1/2} \quad (\text{for } P_f = 1)$$

$$= 0.08 \text{ inch}$$

Thus, the actual physical size of the optics (and any apertures internal thereto) must equal or exceed 0.08 inch in diameter. For lens/mirror availability (in Suprasil 1 optics or equivalent) we would probably use actual lens elements/mirrors of 0.25 inch diameter or larger in order to maintain the use of paraxial rays only.\*\* This would also allow longer lengths of optical fiber transmission lines (greater than 5 meters) to be used, or greater "gain" safety factor if desired.

From equation (6) we find the lens-fiber coupling distance (minimum) to be (assuming a  $D_F = .040$ " fiber):

$$s' = \frac{0.08 - 0.04}{2 \tan 8^\circ}$$

$$= .14"$$

i.e. the fiber end must be at least (but close to) 0.14" from the rear element of the optical system to make full use of  $D_{eff}$ . Any coupling distance ( $s'$ )

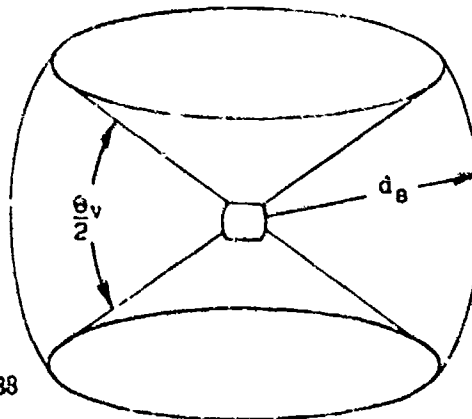
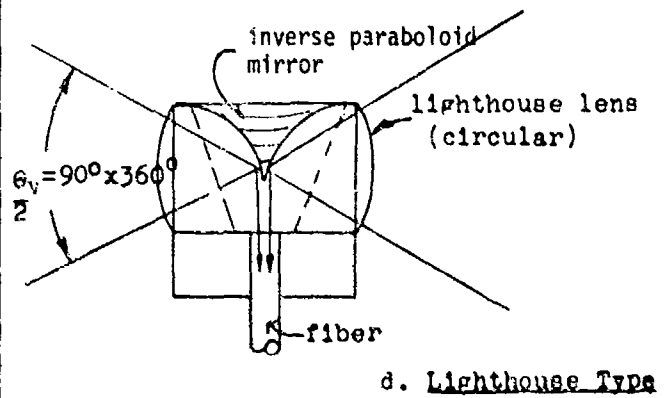
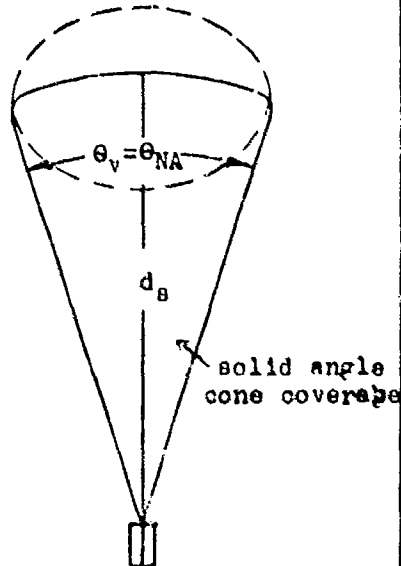
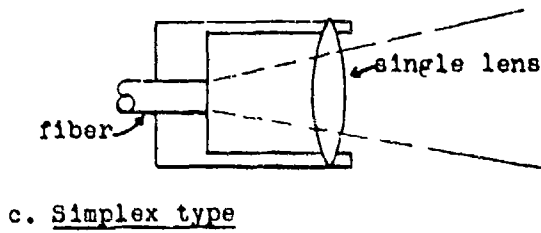
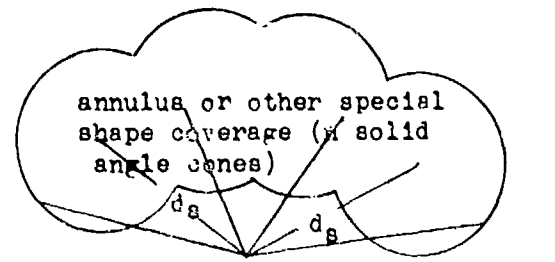
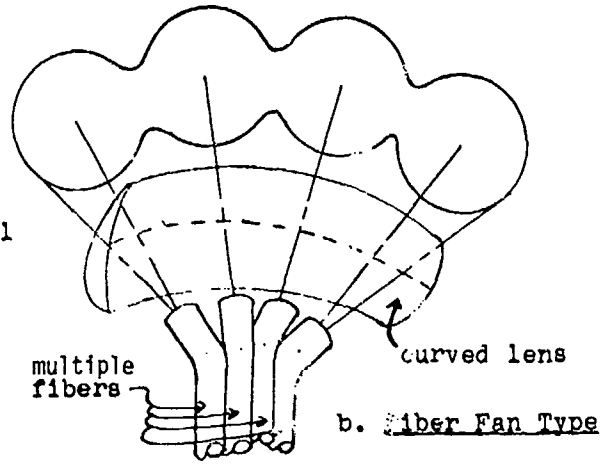
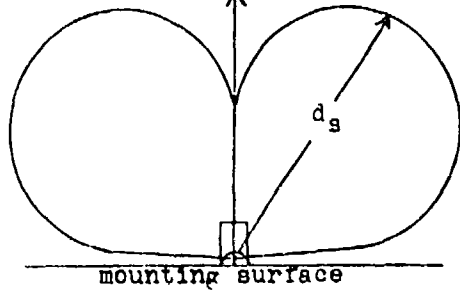
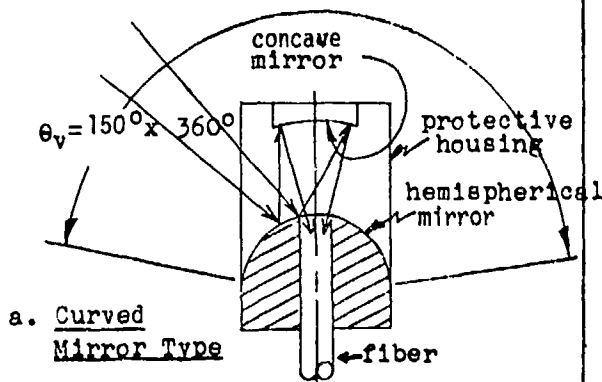
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\* 2 lenses/mirrors in the sensor head plus one lens in the detector coupling optics.

\*\* the use of paraxial rays requires less in lens precision than does the use of full lens/mirror diameters.

Figure 6

SENSOR HEAD CONCEPTS & DETECTION PATTERNS



greater than 0.14" would provide a greater  $D_{eff}$  (and hence greater optical system "gain") and, since we have 0.25" diameter optics available, we'd probably use an  $s' = 0.25$ " or greater, although this would require longer focal length optics. Thus, for calculation purposes, we'll use .14" for  $s'$ .

Now, using equation (7), we find the optical magnification required to match the required field-of-view ( $\theta_v = 150^\circ$ ) to the fiber diameter and acceptance angle ( $D_f = .04$ ",  $\theta_{NA} = 8^\circ$ ) at the fiber-lens separation distance ( $s' = 0.14$ " ):

$$M = 2 \tan^{-1} (0.04/2 \times .14) / 150 = 0.108$$

Thus, an optical system with a fractional magnification ( $M = 0.108$ ), such as that offered by an "inverted telescope" or "fisheye" lens, is required. The focal length for such an optical system is given by equation (8) as:

$$f = \frac{s' d_s}{s' + d_s} = \frac{(.14)(.24)}{24.14} = 0.139 \text{ inch} \quad (\text{or } f = s')$$

If such a focal length were not available in a single lens for the diameter of micro-optics needed, we would probably choose composite optics of appropriate "stock" focal lengths to give a composite focal length approaching 0.14".\*

Such an optical system sensor head is shown schematically in Figure 7. The sizes/dimensions noted are the minimums required, and are probably considerably less than required for ruggedizing the unit to meet military application requirements. However, it is estimated that such units - even when "militarized" - would not exceed 0.5" in diameter x 1.0" length (for the sensor head) and 0.125" diameter for the fiber transmission line (including

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\* the focal length of composite optics is given (approximately) by:

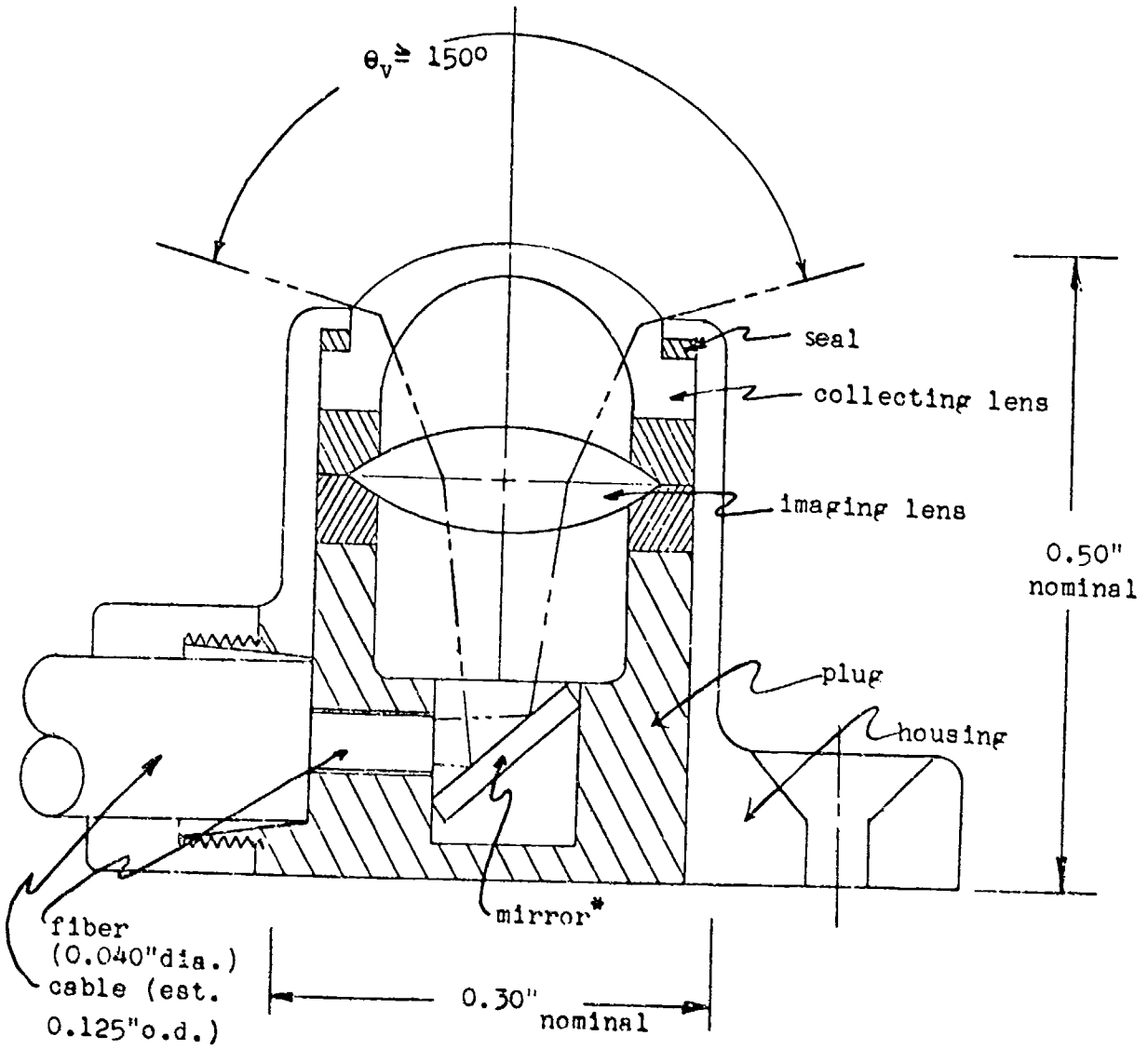
$$\frac{1}{f_T} = \frac{1}{f_1} + \frac{1}{f_2} \quad (\text{evaluated at } \lambda)$$

where each pair of lenses is calculated to give an (interim) equivalent focal length, and then compounded by the above formula to give the overall system focal length. Note that concave lenses have focal lengths that are negative (-f), such that short effective lengths can be attained for the overall system.



FIGURE 7

DISTRIBUTIVE SENSOR HEAD (DSH) - Preliminary Design Concept  
("Fisheye" type lens)



\*if side-entry of fiber required

suitable protective sheathing). The estimated weight of each such sensor unit is on the order of a few ounces, with the fiber transmission line weighing on the order of 1 ounce per meter...or a total sensor/cable weight of just about 1/2 pound per sensor location. A full complement of, say, 10 such sensors (and cables) would provide complete and effective fire surveillance in a typical engine nacelle and, with a total optical "system" weight of only 5 pounds, would weigh far less than the 6 "bare detector" heads now being considered at a weight of some 18 lbs. If 1 of the 6 "bare detector" (dual tube) heads are retained for use with the optical sensor system, and this detector was moved to a cooler operating environment (with an attendant weight reduction possible in both the detector cases and cables - reducing its weight to something like 1 pound ), the weight saving per engine nacelle should be something like  $18 - 5 = 13$  pounds per engine nacelle monitored.

While it is difficult to precisely evaluate the cost tradeoffs at this preliminary stage, rough costs (per sensor channel) should be on the order of:

Optics (2* lenses/mirrors @ \$5)	= \$10	} per sensor head
Fiber (5 meters @ \$2/meter) cable	= \$10	
BASIC PARTS = \$20		

Housing, connectors, assembly and test (MIL qualified)		x10 factor
		\$200/sensor channel
10 channels	x10	
TOTAL		\$2000 per nacelle

Compared to the 5 "bare detector" assemblies that could be eliminated (at a savings of approximately \$1000 each), a net savings of some \$3000 per nacelle should be realizable...and a far greater degree of fire detectivity achieved along with a greatly reduced "false alarms" rate.

While these values are deemed speculative at this stage, they are believed to be within 20% of realizable costs/weight/and volume, as well as performance.

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\* Note that one more lens is required for each detector-fiber group interface-or a total of 22 lenses for a 10-optical sensor system.

For such sensor systems, Figure 8 shows the tradeoffs between a MIL-D-27729A flame detection distance ( $d_s$ ) and fiber cable length ( $L$ ) for various sized optics ( $D_{eff}$ ). Since variations in  $\theta_v$  are achieved in the design of the sensor head optics only, the values shown in Figure 8 apply to "long look" systems as well.

#### "Long Look" Systems

The primary, if not only differences between "long look" systems and those "distributed" systems described above, would be in the sensor head optics (higher optical gain for longer detection range; narrower angles of view) and, perhaps, in the number of such sensor heads required to fill a given "long look" volume. As may be noted from the parametric treatment of  $d_s$  vs  $L$  (as a function of  $D_{eff}$ ) above and in Figure 8, detection ranges of well over 10 feet or more should be achievable with cable lengths of over 5 meters using relatively small optics ( $D_{eff}$  less than 0.5"). Advanced fibers ( $\theta_{NA} = 26^\circ$ ) could provide single lens/mirror systems of slightly lower cost.

A conceptual drawing of a typical "long look" system is provided in Figure 9. Note the method by which overlapping conical areas of coverage could be used to provide large volume area coverage (assuming the intervening space to be free of obstacles). The optics described in the previous section for distributive systems are essentially the same for long-look systems except that the field of view required for "long look" applications may be less than those for DSH. Again, Figure 8 shows the tradeoffs between flame detection range ( $d_s$ ) and optical fiber transmission line length ( $L$ ) as a function of effective aperture ( $D_{eff}$ ) applicable to long-look as well as distributive systems. The larger optics diameters are generally more applicable to the long-look systems since greater optical gain is required to overcome the  $1/d_s^2$  flame-to-lens-distance fall off and/or environmental attenuation encountered in aircraft applications.

Weight, size and cost considerations for long-look systems are essentially the same as those for distributive systems. One possible exception is that, where the acceptance angle ( $\theta_{NA}$ ) of the fibers is sufficient to provide the full angular coverage necessary, then only simple (e.g. one lens or mirror) input optics should suffice. At least one sensor head

FIGURE 8

FLAME\* DETECTION DISTANCE vs FIBER LENGTH

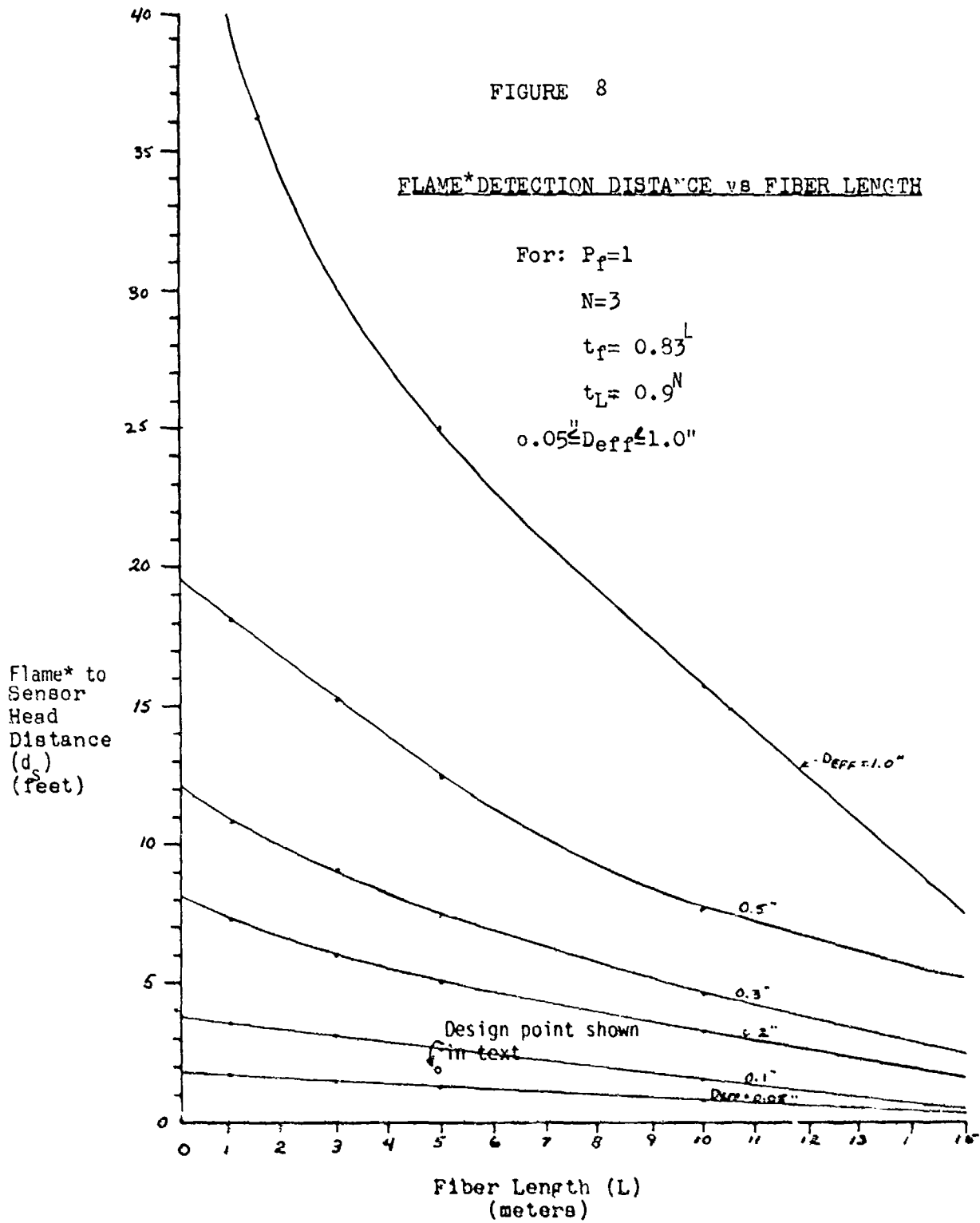
For:  $P_f=1$

$N=3$

$t_f = 0.83^L$

$t_L = 0.9^N$

$0.05 \leq D_{eff} \leq 1.0''$

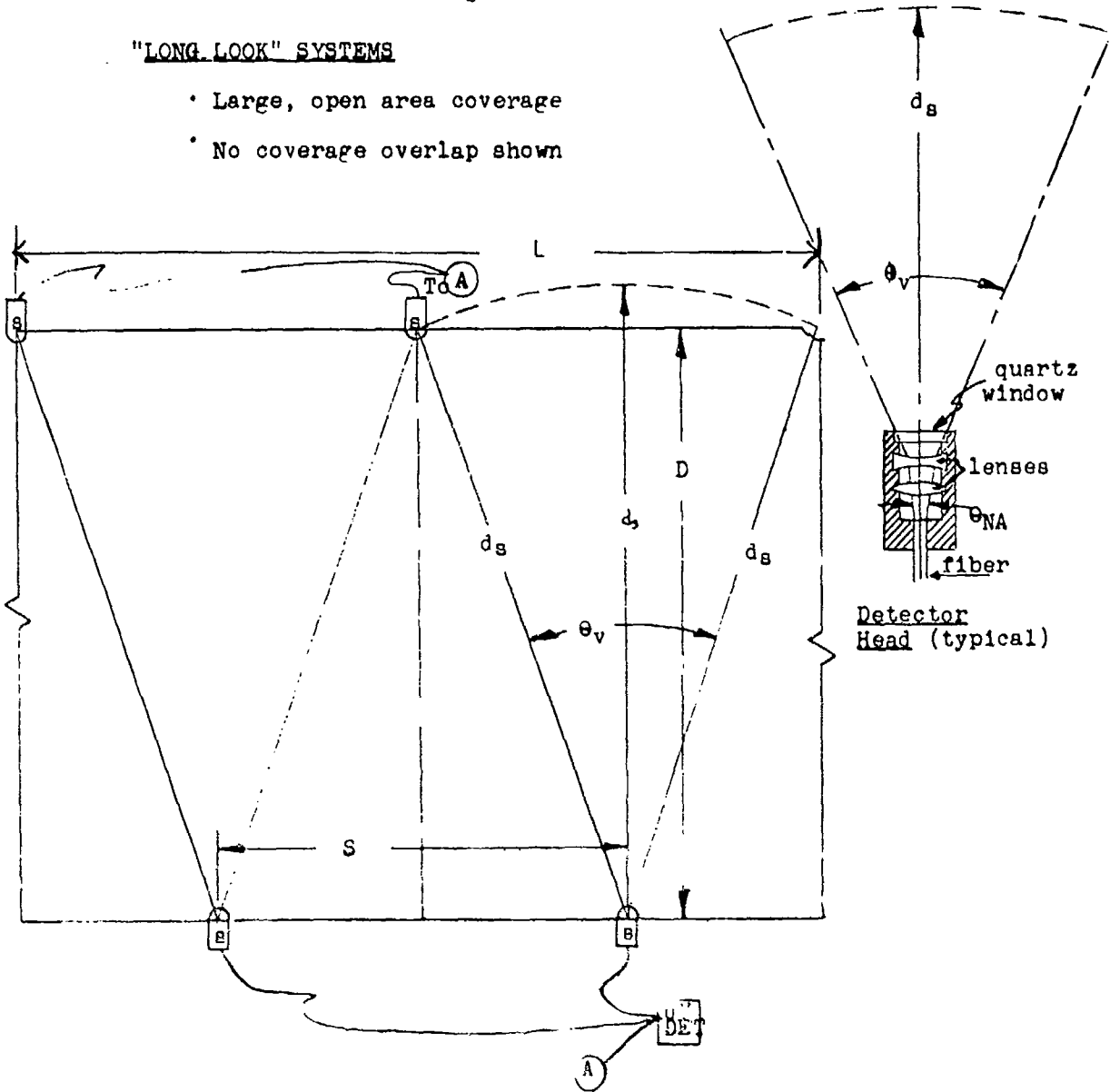


\*MIL-D-27229A standard 5" pan fire (JP-4)

Figure 9

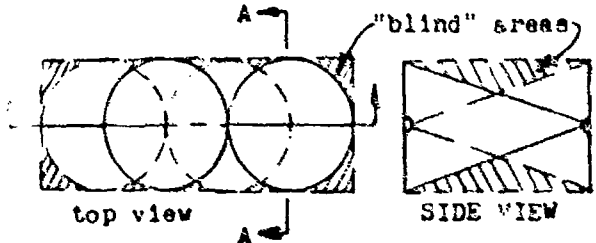
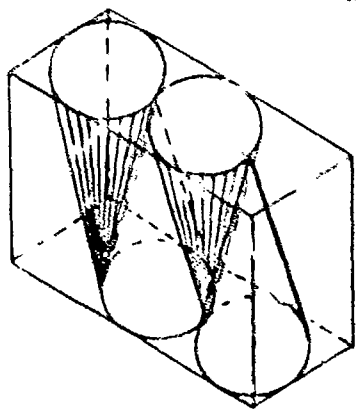
"LONG LOOK" SYSTEMS

- Large, open area coverage
- No coverage overlap shown



$$n_s = \frac{2L}{S} \quad S = 2D \tan \frac{\theta_v}{2} \quad \therefore D \tan \frac{\theta_v}{2} = d_s \sin \frac{\theta_v}{2}$$

$$\text{and } S = 2d_s \sin \frac{\theta_v}{2} \quad \frac{D}{d_s} = \sec \frac{\theta_v}{2}$$



lens or mirror would always be required unless the cross sectional area of the fiber itself (currently limited to 0.001 inch<sup>2</sup> for 0.040" diameter fibers - the largest UV fiber currently marketed) was sufficient to give the gain required. This would result in a fractional "gain" for the system since the effective area of the bare detector is 0.005 inch<sup>2</sup>. Thus the  $d_s$  and fiber length (l) for such "bare fiber" systems would have to be kept very short indeed...much less than 2 feet and 1 meter, respectively, and hence probably would not qualify it in the "long look" category. Under such circumstances, the cost of UV optical elements would probably be about 20-30% less for such long-look systems, although the net overall cost, weight and size savings would probably be negligible.

Since most "long look" applications reviewed (briefly) in this study do not require further thermal isolation of the UV detector (as do many of the distributive system applications), fiber transmission line lengths could be kept short if it were not for the desire to couple as many optical sensor input channels as possible per detector of the sake of cost/weight/volume economy. Only a specific application-oriented analysis can determine such tradeoffs. Since both initial and life system costs, weight, and volume are closely correlated to fiber transmission line length times the number of fibers, if bundles are employed, times the number of sensor heads/transmission lines employed, and, to a far lesser extent, to the input optics employed, suitable tradeoff analyses cannot be performed without knowing 1) specific applications, and 2) the increases in performance (detectivity, surveillance area coverage) desired. However, the fact that optical coupling acts to improve performance in all critical AAFDS system aspects, and to reduce cost, weight, and volume of aircraft fire detection systems specifically, the potential payoffs of such concepts using current state-of-the-art technology seems highly worth while pursuing.

#### Other Optical System Considerations

The following considerations are applicable to all types of optically coupled UV Fire Detection Systems:

1. UV vs. Solar Attenuation - Most optical systems capable of transmitting ultraviolet radiation also transmit radiation of longer wavelengths such as those in the solar visible or IR spectrum. In fact, they do so preferentially (i.e. their attenuation of UV is higher than for visible

wavelengths). As such, the signal (UV) to noise (visible and IR) ratio introduced into the UV detector may well be inverted through the optical system unless proper filtering is employed. This required filtering is easily obtained in the sensor head optical system via the use of appropriate lens coatings or separate UV band-pass filters. All optical designs should include provisions for such filtering in each channel or, at the very least, in the optics coupling the fiber outputs to the UV detector itself. Such filtering should not have an appreciable additional attenuation effect on the desired UV signals, and can even be made to reduce the "other radiation" triggered false alarms induced into "bare detector" systems. Since the UV detectors with optical coupling can now be isolated in lower temperature environments and even shielded against ambient radiation, most false alarm generation should be eliminated other than those false alarms due to voltage transients within the detection system's electronics themselves. By only slightly "over-designing" the optical gain of each channel, the UV detector bias voltage levels and wave form characteristics (e.g. going to DC biasing at lower voltage) can be adjusted to minimize false alarm triggering while maintaining optimal sensitivity to UV reduction.

2. Installation/Maintainability - Optical components, including the fiber transmission lines themselves, are capable of MIL-SPEC ruggedization without too much more difficulty (and in many cases, less) than electrical components. For example, electromagnetic interference (EMI) shielding of optical elements should not be required. A number of non-metallic (i.e. electrically non-conducting) sheathing and ruggedizing techniques are available that can be used to minimize EMI and, at the same time save weight, volume and cost.

Sensor heads can be made of high-temperature metallic or non-metallic materials of sufficient strength to prevent physical damage during maintenance and installation. If the sensor head housing (and, for that matter, the fiber cable sheathing) can be made of a high thermal conductivity material and these components heatsinked to cooler aircraft surfaces such as the back side of subsonic aerodynamic surfaces, much can be accomplished in reducing the ambient temperatures "seen" by the optic system elements. Protective shields can be employed over the sensor optics to protect them from physical damage, scratching, or abrasion just so long as any such protective housing is UV transparent, does not appreciably reduce  $D_{eff}$ , and

are easily removable for periodic cleaning. Removal of UV absorbing films and coatings is a "must" in maintaining optical UV sensor heads at peak performance levels. Accessibility to such heads for cleaning should be a prime consideration in locating the heads within aircraft structures, second only to their basic purpose of being able to "see" fires.

Even with MIL-SPEC ruggedization of optical system components, the weight, volume and cost of such assemblies should still be well below those for "bare detector" systems since 1) no electrical power need be furnished to the optical sensor heads or cables, and 2) even a doubling of weight and volume over the minimum necessary to make the sensors optically effective would still result in much smaller components than those presently associated with "bare detector" systems.

Probably the primary physical-damage mechanism to be associated with optical systems is that of the bending of optical fiber cables in radii smaller than 10 to 20 times the fiber diameter (although for, say, 40mil fibers this is only .4" to .8" radii). Such bends not only could damage (or break) the fibers themselves, but provide UV transmission loss areas in excess of those of straight or long-radius bend runs. The protective sheath for each fiber or bundle can be designed to prevent inadvertent over-bending during installation and maintenance. Considerable care must be exercised in laying out fiber run installations to observe the bend radius restrictions.

3. Optical System Test Provisions - Separate optical fibers may also be used to feed UV test signals to each sensor head or group of sensors. A small (say 4mil) fiber can be run in each fiber transmission cable at little additional cost, weight or volume to feed a UV test signal to each sensor head. The UV test source can be co-located with (but optically isolated from) the UV detector tube. The source can be optically "switched" to each sensor head ( for one-on-one- testing) by either a motorized shutter mechanism or by electronic switching techniques (e.g. Kerr cells or crystal diodes). Since such testing would provide a two-way checkout of not only the sensor head, but of the transmission fiber and test fiber themselves (with no electrical "short circuits" possible\*) such test methods should provide an

---

\* although optical "short circuits" are conceivable, they are nearly impossible due to the absorption of UV by most materials. Optical isolation between the test and return channels is simple and effective.



even greater advantage over electrically connected systems. Any break, over-crimping, or obscuration in either input or return channel would result in a fault indication if the system is designed such that the UV test signal is of equivalent intensity to the sensor threshold detection level. It should be noted that an additional advantage to optical fiber coupled systems would accrue in that breaks in fibers (if their alignment is maintained by the protective sheathing) tend to be self-correcting, unlike electrical cabling, in that UV transmission across such breaks is still possible.

In this and preceding sections of this report we have seen that:

1. The basic "building blocks" (technology) to build a fiber optic coupled aircraft fire detection system exist today and that
2. Using "conventional" UV input optics, more than sufficient gain can be achieved to overcome the transmission losses of significantly long runs of optical fiber cables, and in fact, increase the detectivity of fire detection systems while obtaining significant reductions in cost, weight and volume.
3. Preliminary designs of optically coupled systems strongly indicate that optically coupled fire detection systems can be built and tested without major additional developments.

A summary comparison of optically coupled vs "bare detector" systems is shown in Table 3.

TABLE 3: COMPARISON OF FIBER OPTICS COUPLED UV AAFDS WITH BARE DETECTOR SYSTEMS  
 (+=advantage, -=disadvantage, .= equivalent)

Fiber Optics Coupled Systems	"Bare Detector" Systems
<ul style="list-style-type: none"> <li>+ Permits relocation of UV detector to more benign environment to reduce false alarms, increase sensitivity</li> </ul>	<ul style="list-style-type: none"> <li>+ Large (90°) "look" angles without optics</li> </ul>
<ul style="list-style-type: none"> <li>- Small effective area and "look" angles (without associated optics)</li> </ul>	<ul style="list-style-type: none"> <li>+ Mechanically qualified to meet aircraft environments and conditions</li> </ul>
<ul style="list-style-type: none"> <li>+ Permit multiple sensor locations per UV detector tube (fan out)</li> </ul>	<ul style="list-style-type: none"> <li>- Multiple area coverage costly (\$, weight, space)</li> </ul>
<ul style="list-style-type: none"> <li>+ Reduced system cost, complexity, size, weight, power requirements, electrical power distribution in sensitive areas</li> </ul>	<ul style="list-style-type: none"> <li>- Detectivity reduced/false alarms increased in high temperature environments (could improve in cooler environment)</li> </ul>
<ul style="list-style-type: none"> <li>+ Installation flexibility provides greater area coverage</li> </ul>	
<ul style="list-style-type: none"> <li>- Transmission losses proportional to length of fiber (but may be compensated by optical gain up to practical limits)</li> </ul>	
<ul style="list-style-type: none"> <li>- Compatibility with aircraft environments/ conditions not yet established</li> </ul>	
<ul style="list-style-type: none"> <li>+ Permits increased detectivity (range, look angles) over "bare" detectors</li> </ul>	
<ul style="list-style-type: none"> <li>+ Field (and range) of view may be tailored to meet aircraft space surveillance characteristics</li> </ul>	

## SECTION IV

### CONCLUSIONS AND RECOMMENDATIONS

In this review of the state-of-the-art of fiber optics and related subsystem components, and in assessing their applicability to aircraft UV fire detection systems, we have shown that optics can aid the fire detection system designer in improving his system in many ways:

1. By permitting him to move the UV detector tube to a more benign environment (especially lower temperature and reduced ambient radiation outside the UV spectrum), thus permitting greater detector sensitivity while, at the same time, reducing the "false alarm" rate.
2. By enabling one UV detector tube to monitor a large number of fire-potential positions via fiber-coupled optical sensors.
3. By permitting a variety of adaptive sensor head input optics designs that can be tailored to meet the specialized needs of aircraft fire detection area surveillance.

#### 4.1 CONCLUSIONS

Although the recent emphasis in optical fiber development has been in the communications area and not, per se, in the UV region, a number of fibers and all other required sub-system components suitable for aircraft fire detection system development responsive to the requirements for an Advanced Fire Detection System (AAFDS) are currently available from a number of manufacturers. Some of these fibers have temperature ratings of up to 250°C while all other components are rated well above this temperature, and thus are within the range required for AAFDS applications.

Although little additional work has been done over the past decade on magnesium fluoride ( $MgF_2$ ) clad fibers, the great progress in fiber core development using other cladding methods, and the advancements in the use of  $MgF_2$  as an optical coating agent in general optics are greatly encouraging in that a combination of these technologies (UV fiber core materials and  $MgF_2$  cladding) could provide a high-temperature (well in excess of 300°C), low loss ( $t_f \geq .8 L$ ), and, most important, high numerical aperture ( $NA = 0.44/\theta_{NA} \approx 26^\circ$ ) fiber for AAFDS should presently available fibers be limited in some way not known through analytical means such as those used in this study.

Yet the aircraft fire detection system designer need not wait for the development and production of  $MgF_2$  or other similarly clad high-performance fibers to begin development and testing of fiber-optically coupled systems. The presently available fibers and other subsystem components strongly suggest that the technology is here - now - to begin actual development and testing of optically coupled systems. Optical systems can increase both the detection range and view angle of unaided "bare detectors" while, at the same time, achieving significant reduction in cost, weight, volume and complexity of aircraft fire detection systems. When (and if) more advantageous fibers become available, they can be directly "plugged in" to properly designed optical sensor heads and UV detector tube coupling optics on a 1-to-1 replacement basis.

#### 4.2 RECOMMENDATIONS

A pilot (prototype) fiber optic coupled UV fire detection system program should be instituted to evaluate the concepts and analytical findings presented in this report. The objectives of this program should include:

1. The critical design, development and testing of a prototype fiber optic system using current state-of-the-art technology.
2. Evaluation of the achievable increases in performance, and reduction of cost, weight and volume of such optically coupled systems and their related payoffs in terms of reduced false alarm rates, increased detector sensitivity, and improvements in associated fire detection system electronics.
3. Identifying (and, if necessary, promoting) specific subsystem element developments (e.g. fibers, optics, detectors) that can be used to further enhance the overall effectiveness and efficiency of aircraft fire detection systems.
4. Demonstration of the performance of integrated optically-coupled UV fire detection systems - by actually building and testing hardware in aircraft operational environments.

## REFERENCES

- 1/ Pontarelli, Li, and Olson, ULTRAVIOLET FIBER OPTICS FOR FIRE AND EXPLOSION DETECTION, AFAPL-TR-67-31, 1967.
- 2/ Sommers, D.E. and O'Neill, J.H., AFAPL AIRCRAFT FIRE TEST PROGRAM WITH FAA 1967-1970, AFAPL-TR-70-93, 1971.
- 3/ Suminski, Riemer, and Hankey, INTEGRATED FIRE AND OVERHEAT DETECTION SYSTEM, AFAPL-TR-76-64, 1976.
- 4/ Sommers and O'Neill, loc cit. (Ref 2/) The tests described, while conducted by FAA, were for the AFAPL.
- 5/ O'Neill, Sommers, and E.B. Nicholas, AEROSPACE VEHICLE HAZARD PROTECTION TEST PROGRAM: DETECTORS: MATERIALS: FUEL VULNERABILITY, AFAPL-TR-73-76, 1974.
- 6/ United States Air Force Systems Command, RFQ F33615-77-R-2029, ADVANCED AIRCRAFT FIRE DETECTION SYSTEM, 1976.
- 7/ Buyken, H. and Kriege, W., "Properties of UV-Fibers", OPTICAL ENGINEERING, July/August 1973, Vol. 12, No. 4.
- 8/ Linford, R.M.F., Dillow, C.F., and Trumble, T.M., "Optical Emissions from Burning Jet Fuel," JOURNAL OF AIRCRAFT, Vol. 14, No. 5, May 1977.
- 9/ Pomerantz and Godwin, "Ruggedized Fiber Optic Cables for Army Communications Systems," SOCIETY OF PHOTO-OPTICAL INSTRUMENTATION ENGINEERS PROCEEDINGS, Vol. 77, March 1977.
- 10/ RCA, PHOTOMULTIPLIER MANUAL, Technical Series PT-61, 1970 (Rev.).

APPENDIX A

Selected Samples of  
Manufacturers Data on Fiber  
Optics and Components

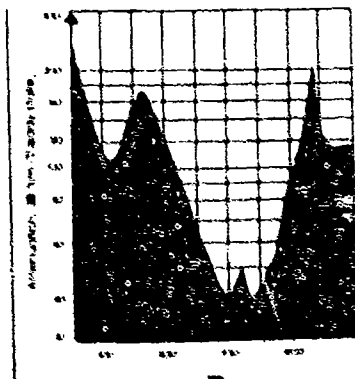
## Properties of Du Pont PFX-S Silica Core Fiber Optic Cables

PFX-S12OR is a single channel plastic clad silica fiber optic cable. Its large diameter single fiber is protected by jackets of Hytrel® polyester elastomer and Kevlar® aramid fiber to give this cable outstanding strength and ruggedness.

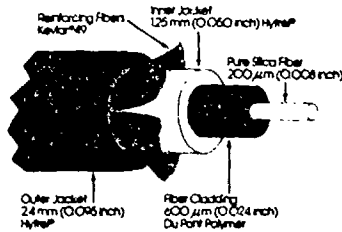
PFX-S22OR is a dual channel plastic clad silica fiber optic cable designed for two-way communication and protected in the same manner as the single channel cable described above which provides outstanding resistance to physically hostile environments.

The large active diameter and large numerical aperture of the fiber provide easy and efficient coupling even with inexpensive connectors. The silica core is well centered within a tough hard cladding to which a connector can be crimped directly. The black pigmented jacket provides UV resistance. We believe it is among the most rugged silica fiber cables currently available. Run lengths up to one kilometer are possible depending on the source, connectors, and receiver.

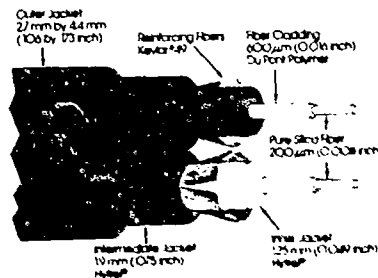
### Maximum Spectral Attenuation



### PFX-S12OR



### PFX-S22OR-600



### Typical Properties of PFX-S Optical Fibers

Maximum Attenuation:  
40 dB/km at 775 nm  
50 dB/km at 820 nm

Numerical Aperture  
(Material NA) 0.4 (calculated)

Exit Numerical Aperture  
(Radiation  
Pattern NA) 0.27 at 10 dB down

Core Refractive Index 1.456

### Typical Properties of PFX-S Cables

Tensile Strength<sup>1</sup> - S12OR 65 kg  
- S22OR 130 kg

Cable Weight - S12OR 6 kg/km  
- S22OR 10 kg/km

Minimum Bend Diameter<sup>2</sup>  
(short term) - S12OR 3.0 mm

Flex Resistance<sup>3</sup> - S12OR 10,000 cycles

### Notes on Test Methods:

1. Steady state values beyond the 250 meter coupling length.
2. The strength at which the optical fiber breaks in a one meter test length. Ends wrapped around 1.6 cm radius mandrel.
3. Can be wrapped five times around a 3.0 mm diameter mandrel with no fiber breakage.
4. Proposed MIL-STD-1678-Method 2010.

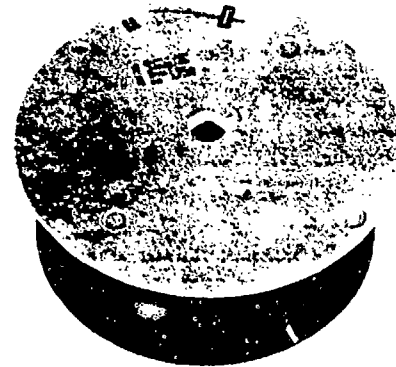
This product is believed to be suitable for the environment of typical laboratory applications where fiber optic materials are being considered. Where severe industrial or military applications are being contemplated, the designer should consult Du Pont for the latest laboratory exposure data that will assist him to estimate the performance of this cable during the expected life of the system. For example, the optical fiber still meets the attenuation specifications after fifteen months immersion in water at room temperature and is still being tested. The jacketed cable meets attenuation specifications at 820 nm after 12 days exposure at 70°C/90% RH.

### Prices and Terms

Standard Plastic Core Cables  
PFX-P140  
(single channel) \$1.50 meter  
PFX-P240  
(two channel) 3.00 meter  
Infrared Transmitting Plastic  
Core Cable  
PFX-PR120 (single channel  
deuterated plastic) 2.25 meter  
Visible-IR Transmitting Plastic  
Clad Silica Core Cables  
PFX-S120  
(single channel) 2.25 meter  
PFX-S220  
(two channel) 5.20 meter  
The minimum order for each cable  
type is 100 meters.  
Terms: Net 30 days delivered  
Overseas shipments are FOB origin.

# Low-Loss, Large Diameter Silica Core, Step-Index Single-Strand Optical Fibers

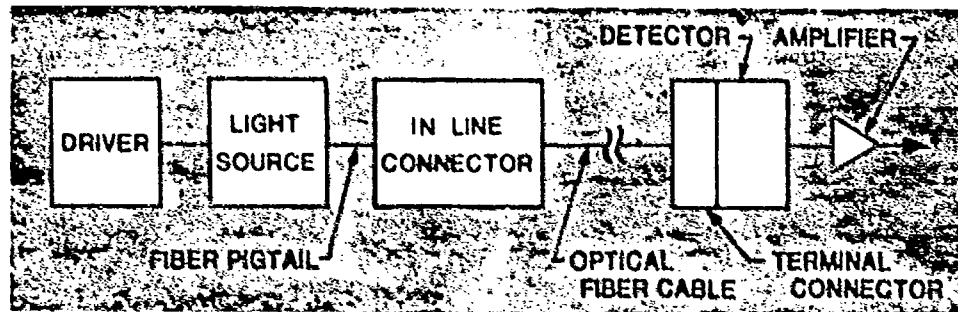
- Easy Coupling to LED's, Detectors
- Long Lengths to 10 Km
- High Tensile Strength & Flexibility
- Large Diameter Single-Strand Fiber replaces "bundles", especially for ir and uv applications
- "Best Available" low-loss fiber for nuclear radiation resistance
- Excellent laser power handling
- High Flexibility, High Temperature Tefzel Coating



All QSF-A materials exhibit attenuations of less than 5 db/Km at 0.85 um.

Starting with large ingots of extremely pure fused silica, Quartz Products is able to offer a range of large diameter, long length optical fibers with many important advantages. Large ingot size permits drawing 10 Km lengths and longer in large diameters. High purity keeps attenuation low in the

ultraviolet, visible and infrared regions. Recovery from nuclear radiation is reported as "equal to the best" by government sources. With the high purity of fused silica, both strength and stress-elongation are extraordinarily high, permitting great ease in handling and cabling.



Typical Fiber Transmission System. Upon request, QPC will provide names of component manufacturers, cable producers and system assemblers using QSF-A Series fiber.



Quartz Products Corp.  
688 Somerset St.,  
Plainfield, New Jersey 07061  
(201) 757-4545





**Specifications**

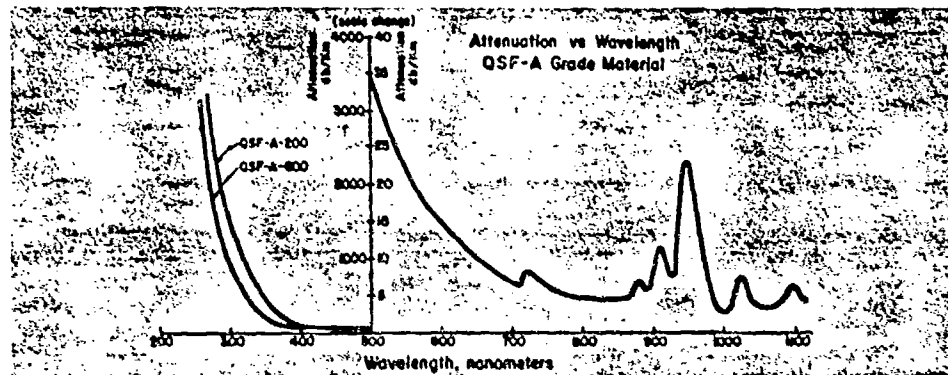
Fiber	Core Diameter um	Standard Silicene Cladding um O.D.	Standard Tefzel Coating um O.D.	Maximum Uncut Length Km	Maximum Attenuation at 0.85 um db/Km	Numerical Aperture	3 db Optical Bandwidth MHz-Km	Tensile* Strength Kpsi	Minimum Bending Radius mm
QSF-A-200	200	400	600	10	5	0.22	25	500	3
QSF-A-300	300	440	650	6	5	0.22	20	500	10
QSF-A-400	400	550	850	5	5	0.22	15	500	12
QSF-A-600	600	750	1060	3	5	0.22	9	500	15

\*on short lengths

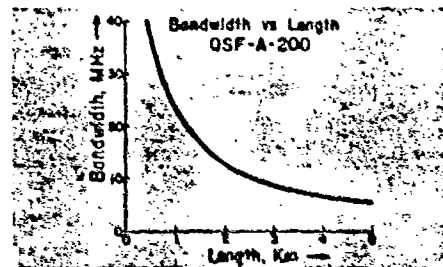
**Notes:**

1. Both "B" and "HA" series are available with attenuations of  $\leq 10$  db/Km and  $< 100$  db/Km respectively, offering high economy where the greater attenuations can be tolerated.
2. Cladding and coating diameters may be reduced for special fiber O.D. requirements.
3. Both 100 um and 1000 um core diameter fibers are also available on request.

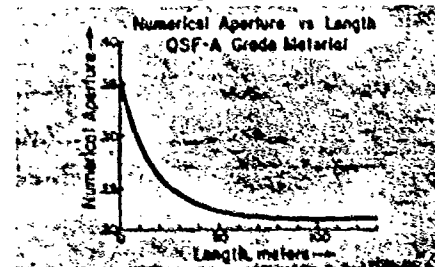
**Attenuation**



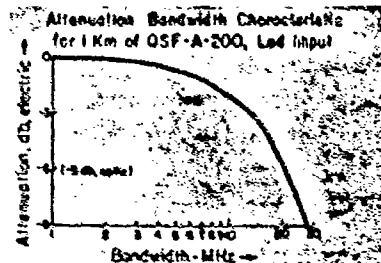
**Bandwidth**



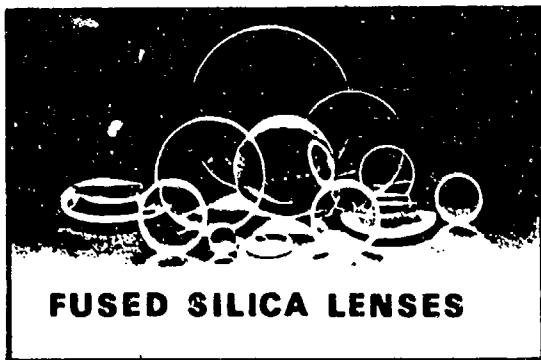
**Numerical Aperture**



**Attenuation-Bandwidth Characteristic**



Quartz Products Corp.  
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Plainfield, New Jersey 07061  
(201) 757-4545



Fused silica is an ideal optical material for many applications. It is extremely transparent over a wide spectral range, has a low coefficient of thermal expansion, and is resistant to scratching and thermal shock.

Synthetic fused silica (amorphous silicon dioxide) is formed by chemical combination of silicon and oxygen. It is not to be confused with fused quartz which is made by crushing and melting natural crystals. Synthetic fused silica is far purer than natural materials. This increased purity assures higher ultraviolet transmission, better homogeneity, and freedom from striae or inclusions.

When compared with glass or fused quartz, fused silica lenses offer a number of advantages:

1. Greater UV and IR transmission.
2. Low coefficient of thermal expansion, providing stability and resistance to thermal shock over large temperature excursions.
3. Higher thermal operating range.
4. Increased hardness and resistance to scratching.
5. Much higher resistance to radiation darkening from UV, x-rays, gamma rays, and neutrons.

Manufacture of fused quartz by crushing and melting natural crystalline quartz, or by fusing silica sands, results in a granular microstructure and bubble entrapment. Microstructure and impurities lead to local index variations, and contribute, along with bubbles and opaque particles, to reduced transmission throughout the spectrum. The synthetic fused silica materials we offer are manufactured by flame hydrolysis to extremely high standards. The resultant material is colorless and non-crystalline. Suprasil 1 has an impurity content of about one part per million. Controlling the purity of the reactants and conditions of reaction (rather than simply remelting natural materials) assures the high quality of the synthetic fused silica from which we make our lenses.

Optical Quality Synthetic Fused Silica lenses are ideally suited for applications in energy gathering and imaging systems in the mid-UV, visible and near IR. They will, in all respects, outperform simple fused-quartz or glass lenses with similar parameters.

Suprasil 1 is the best grade of synthetic fused silica commercially available for ultraviolet and visible applications. It offers both the highest transmission (especially in the deep ultraviolet), and very low fluorescence levels (approximately 0.1% that of fused natural quartz excited at 254nm). Suprasil 1 does not fluoresce in response to wavelengths longer than 290nm. In imaging systems, and in deep-UV applications, Suprasil 1 is the ideal choice. Its homogeneity, as evidenced by the tight index tolerance, results in improved image quality and highly predictable lens specifications.

Abbe constant:  $67.6 \pm .5$

Change of refractive index with temperature (0 to 700°C):  
 $1.38 \times 10^{-5}/^{\circ}\text{C}$

Homogeneity (Maximum index variation over 10cm aperture): Suprasil 1 is  $6.6 \times 10^{-6}$ , Optical Quality is  $20 \times 10^{-6}$

Obscuration (Maximum average percent from bubbles, inclusions and striae per cm thickness): Suprasil 1 is 0.001%, Optical Quality is 0.01%

Continuous operating temperature: Maximum 950°C

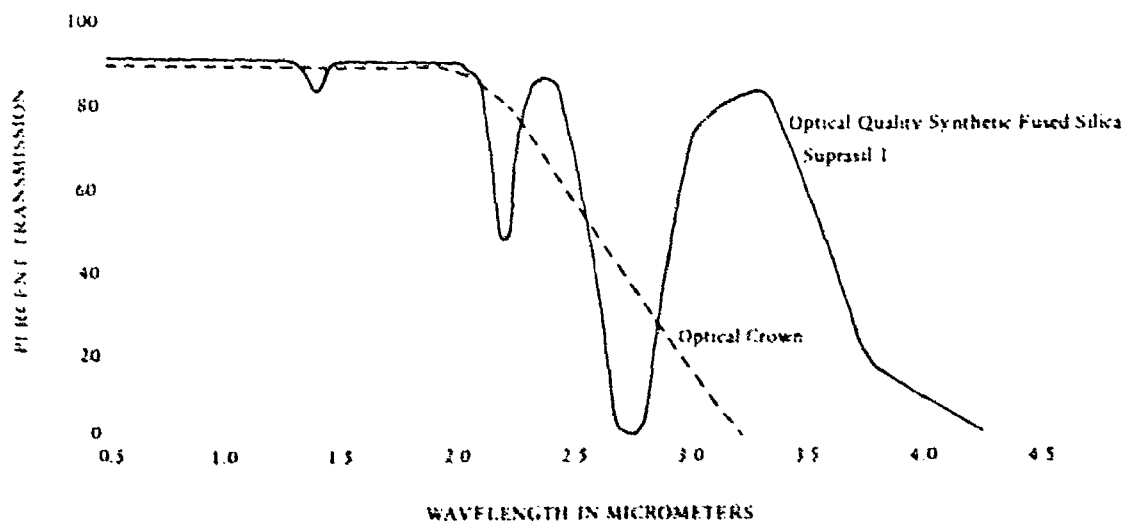
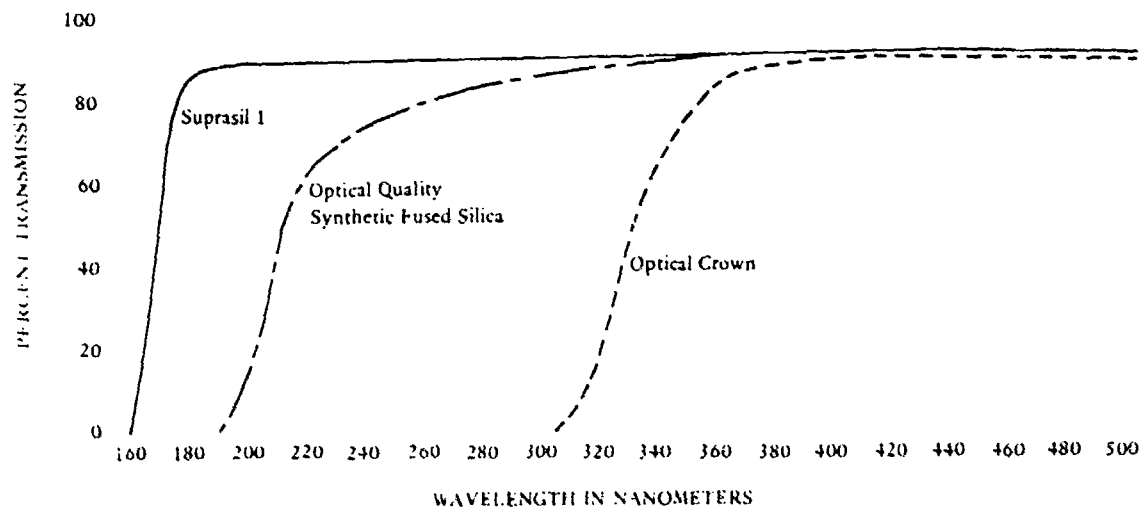
Coefficient of thermal expansion:  $5.5 \times 10^{-7}/^{\circ}\text{C}$

Thermal conductivity (100°C):  $0.0035 \text{ cal sec}^{-1} \text{ cm}^{-1}\text{C}^{-1}$

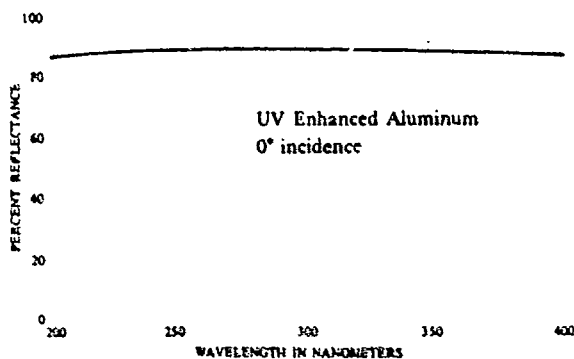
The following table shows the refractive index of Suprasil 1 versus wavelength at 20°C. To obtain index for Optical Quality Synthetic Fused Silica, round the following values off to the fourth decimal place. Accuracy of index  $\pm 3 \times 10^{-5}$

(nm)	n	(nm)	n	(nm)	n
202.54	1.54717	280.35	1.49403	361.17	1.47503
206.20	1.54266	289.36	1.49098	365.45	1.47448
213.85	1.53434	298.06	1.48837	404.65	1.46961
226.50	1.52299	307.59	1.48575	435.83	1.46669 ( $n_g$ )
237.83	1.51473	313.17	1.48433	486.13	1.46314 ( $n_F$ )
248.20	1.50841	334.15	1.47976	546.07	1.46007 ( $n_e$ )
257.62	1.50351	340.36	1.47860	587.56	1.45847 ( $n_d$ )
265.36	1.49994	346.69	1.47748	656.27	1.45637 ( $n_C$ )

TRANSMISSION FOR SUPRASIL 1, OPTICAL QUALITY SYNTHETIC FUSED SILICA AND OPTICAL CROWN GLASS  
0.9mm material thickness - surface reflections included



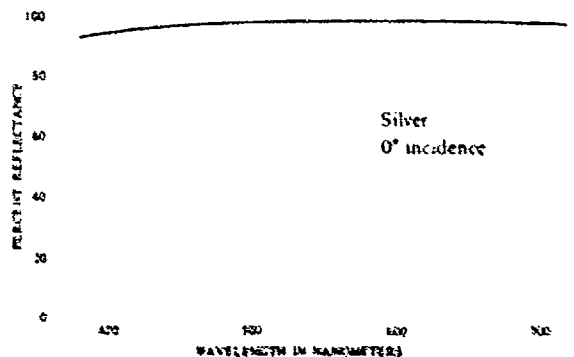
Append 1028 to product number of object to be coated.



#### ULTRAVIOLET-ENHANCED ALUMINUM

By applying a film of an ultraviolet-transmitting dielectric (usually  $MgF_2$ ), the reflectivity of pure, bare aluminum can be preserved in the ultraviolet. The dielectric layer prevents oxidation of the aluminum surface and provides abrasion resistance. While the resulting surface is not as abrasion-resistant as our protected aluminum, this coating may be cleaned with care. Reflectance averages over 88% from 180nm to 400nm, and over 85% throughout the visible. This coating can be applied to all of our mirrors with the exception of the paraboloidal and ellipsoidal reflectors.

Append 1036 to product number of object to be coated.



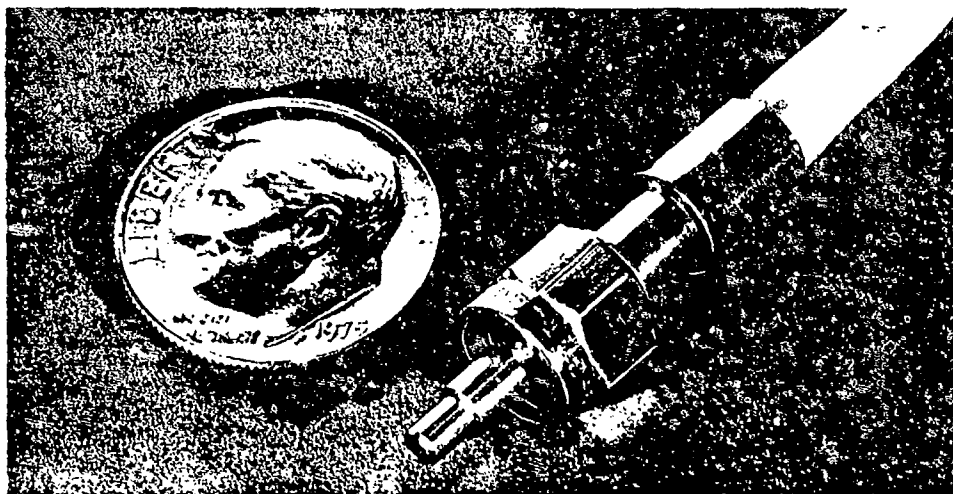
#### SILVER (for use in internal reflection only)

Through most of the visible and in the near infrared, silver has higher reflectance than aluminum, at least for a short time following deposition. Because the advantage is temporary, silver is rarely used in external reflection. Instead, silver is used almost exclusively in internal reflection. Oxidation and tarnish are prevented by overcoating the external surface with an additional layer of either Inconel or copper. The Inconel or copper layers are subsequently painted to increase abrasion resistance. In this way the high initial reflectance of silver is indefinitely preserved.

Silver is frequently used in the near infrared (the interval containing the neodymium and gallium arsenide laser lines), because it avoids the small dip in reflectance which aluminum exhibits in this interval. In the near ultraviolet, silver has very low reflectance, and aluminum is a preferable choice. From the visible into the middle infrared, silver offers the highest internal reflectance available from a metallic coating. Silver has a lesser effect than aluminum on polarization state in these parts of the spectrum.

**BUNKER  
RAMO** **AMPHENOL**  
**RF PRODUCT NEWS**

**PRECISION OPTICAL CONNECTOR  
FOR SINGLE FIBER CABLE  
AMPHENOL 906 SERIES**



**AMPHENOL 906\* SERIES  
SINGLE FIBER TERMINATION**

The increasing popularity of single fiber cable in optical data transmission systems is one of the primary factors behind the development of Amphenol's new 906 Series connectors.

These single fiber connectors are designed to support improved system performance and specifically offer reduced signal losses, repeatability and low cost.

Since loss characteristics are directly related to accurate alignment of the fiber, particular design consideration was given to three critical areas yielding a 1.5-2.0 dB termination.

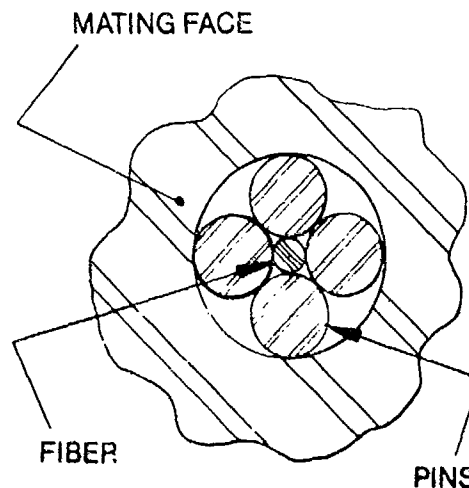
**TYPICAL SPECIFICATIONS**

Lateral Displacement: .0002" maximum  
Angular Displacement: Less than 1°  
End Separation: .0001" minimum to  
.0013" maximum

Our 906 Series terminates several of the popular single fibers presently offered by manufacturers such as: Galileo; ITT; SIECOR; Times; Valtec.

IN PRECISION FIBER OPTIC CONNECTORS, THE NAME AMPHENOL AND STATE-OF-THE-ART ARE SYNONYMOUS.

\*Patent applied for.



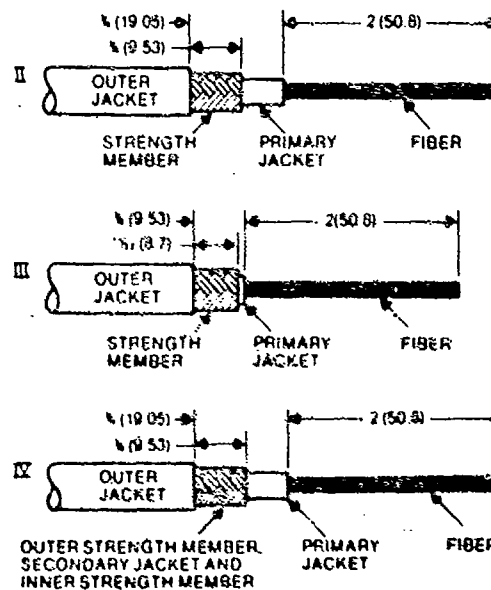
**ENLARGED VIEW  
OF 906 SERIES  
MATING FACE SHOWING  
POSITIONING PINS  
FOR PRECISELY LOCATING  
OPTICAL FIBER**

PRECISION OPTICAL TERMINATIONS FOR SINGLE FIBER OPTICAL CABLE

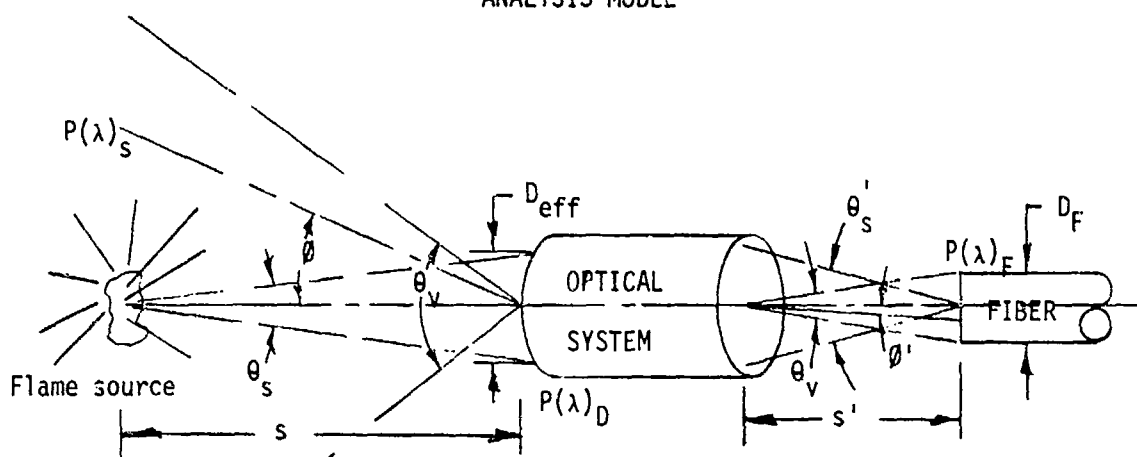
AMPHENOL 906 SERIES

SINGLE OPTICAL CABLE	CABLE DATA, Inches (millimeters)				AMPHENOL NUMBER	CABLE STRIPPING DWG.
	FIBER O.D.	PRIMARY JACKET O.D.	SECONDARY JACKET O.D.	OUTER JACKET O.D.		
CORNING/SIECOR 1352	.005 (.125)	.055 (1.400)	.120 (3.048)	.197 (5.000)	906-110-5000	IV
CORNING/SIECOR 1353	.005 (.125)	.055 (1.400)	.120 (3.048)	.197 (5.000)	906-110-5000	IV
<b>TIMES FIBER COMMUNICATIONS</b>						
GP1/GA10-90	.005 (.125)	.062 (1.575)	—	.117 (2.972)	906-110-5001	II
GP1/GA15-90	.005 (.125)	.062 (1.575)	—	.117 (2.972)	906-110-5001	II
GP1/SA7-90	.005 (.125)	.062 (1.575)	—	.117 (2.972)	906-110-5001	II
GP1/SA10-90	.005 (.125)	.062 (1.575)	—	.117 (2.972)	906-110-5001	II
HT1/GA10-90	.005 (.125)	.062 (1.575)	—	.117 (2.972)	906-110-5001	II
HT1/GA15-90	.005 (.125)	.062 (1.575)	—	.117 (2.972)	906-110-5001	II
HT1/SA7-90	.005 (.125)	.062 (1.575)	—	.117 (2.972)	906-110-5001	II
HT1/SA10-90	.005 (.125)	.062 (1.575)	—	.117 (2.972)	906-110-5001	II
<b>ITT</b>						
S-6-GG-(1)	.005 (.125)	.020 (.500)	—	.098 (2.500)	906-110-5001	II
S-10-GG-(1)	.005 (.125)	.020 (.500)	—	.098 (2.500)	906-110-5001	II
S-20-GG-(1)	.005 (.125)	.020 (.500)	—	.098 (2.500)	906-110-5001	II
S-6-GS-(1)	.005 (.125)	.020 (.500)	—	.098 (2.500)	906-110-5001	II
S-10-GS-(1)	.005 (.125)	.020 (.500)	—	.098 (2.500)	906-110-5001	II
S-20-GS-(1)	.005 (.125)	.020 (.500)	—	.098 (2.500)	906-110-5001	II
<b>VALTEC</b>						
NHU-MS05-01	.005 (.125)	.125 (3.175)	—	.210 (5.334)	906-110-5003	III
NHU-MG05-01	.005 (.125)	.125 (3.175)	—	.210 (5.334)	906-110-5003	III
<b>GALILEO</b>						
5000C-1S	.005 (.125)	.088 (2.235)	—	.165 (4.191)	906-110-5005	III

CABLE STRIPPING DIMENSIONS DRAWINGS  
Inches (millimeters)



APPENDIX B  
ANALYSIS MODEL



Let...

$\theta_s$  and  $\theta'_s$  = angles subtended by optical system from fire (source and fiber (image))

$\theta_v$  and  $\theta'_v$  = field of view angles within object space and image space such that the ratio  $\theta'_v/\theta_v = M$  is the angular magnification of the optical system

$s$  = flame to optical system distance

$s'$  = optical system to fiber distance

$\theta$  and  $\theta'$  = the flame and image offset angles from the optical system center line

$D_{eff}$  = the effective diameter (aperture) of the optical system

$D_F$  = fiber diameter (i.e. the image space)

$T$  = lumped transmission coefficients of the optical system (including fiber and detector coupling)

$P(\lambda)$  = the power density (UV) at the designated subscript point ( $s$ =flame,  $D$ =optical system head,  $F$ =fiber)

Of the total power radiated from the source ( $P(\lambda)_s$ ) over  $4\pi$  steradians, subtending the optical system's input optics, in the unit solid angle subtended by the lens is  $\pi D_{eff}^2/4s^2$ , or the power delivered by the flame to the optical system input is:

$$P(\lambda)_D = P(\lambda)_s \pi D_{eff}^2/4s^2$$

If energy is conserved within the optical system (including losses according to the transmission coefficient, T), then the energy delivered through the optical system (including fiber and detector coupling optics) may be expressed as:

$$P(\lambda)_s = \pi D_{\text{eff}}^2 T / 4 s_s^2$$

By similar analysis, the power delivered by the same flame to a bare detector filament at a distance s, is proportional to the solid angle subtended by the filament,  $A_f$ , at a distance s, or:

$$P(\lambda)_f = A_f / s_f^2$$

Since the area of the filament is known ( $A_f = 0.01" \times 0.5" = 0.005 \text{ in}^2$ ), we can find the power gain (or loss) offered by the optical system as:

$$\frac{P(\lambda)_s}{P(\lambda)_f} = \frac{\pi D_{\text{eff}}^2 T s_f^2}{4 A_f s_s^2}$$

But  $\pi D_{\text{eff}}^2 / 4$  is the effective area,  $A_{\text{eff}}$  of the optical system. Thus, we can write a generalized expression for the power gain of the optical system relative to that of the bare detector as:

$$\frac{P(\lambda)_s}{P(\lambda)_f} = \frac{A_{\text{eff}} T s_f^2}{A_f s_s^2}$$

Substituting numerical values and normalizing this relationship from the standard "bare detector" calibration (test) distance of 4 feet from the 5 inch JP-4 pan fire flame gives the values shown in equation 5 in the text.

From optics we know, by definition, that the angular magnification of an optical system may be defined as the angular offset an object (in the image space) yields to the image offset (in the image space); or, in terms of object and image size, as a ratio of the size of the image to the object (taking into consideration the angular magnification); or, by triangle similarity (for simple lenses) the ratio of the optical system spatial geometry distances of lens to object and image, respectively. Thus, if  $M_\theta = \theta'_V / \theta_V$  is the angular magnification, then:

$$M_L = M_\theta s' / s = M_\theta x' / x \text{ where } x' \text{ and } x \text{ are the dimensions of the image and object, respectively.}$$



From this relationship, we can see that an object of dimension  $x$  in the object space will be magnified (or, as we shall want, demagnified, i.e.  $M_\theta$  and  $M_L \ll 1$ ) both in size and relative position (viz a viz the optical axis). Since all of the energy (power) in the system is conserved (exclusive of transmission losses), the image size-and its position-can be controlled through optical design to remain in the fiber area through a wide range of offset angles (up to  $\theta_v$ ).

By geometry (of the optical system's output) we can see that the relationship between the fiber diameter (i.e. image space,  $D_F$ ) and the effective area of the lens (as limited by the fiber's inability to accept radiation at an incidence angle greater than  $\theta_{NA}$ ) may be expressed as:

$$\frac{D_{\text{eff}} - D_F}{2s} = \tan \left( \frac{\theta'_s}{2} \right)$$

But  $\theta'_s/2$  is the angle of incidence of the rays entering the fiber. By definition of  $\theta_{NA}$ ,  $\theta'_s/2$  must be less than or equal to the half angle of incidence,  $\theta_{NA}$ . Thus we can rewrite the above equation as:

$$D_{\text{eff}} = D_F + 2s \tan \theta_{NA}$$