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CONCEPTUAL DEVELOPMENT OF THE LASER BEAM MANIFOLD (LBM)

By Warren Campbell and Robert B. Owen
Space Sciences Laboratory

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Page 2: In the sixth line above equation (1), change the word "exist" to "exit." In the second line above equation (1), change the symbol for index of refraction from "n" to "n_R". (This is to distinguish index of refraction from the total number of beams elsewhere in the report.) Also change equation (1) to:

$$S = \frac{2d \sin \theta_i \cos \theta_i}{\sqrt{n_R^2 - \sin^2 \theta_i}} \tag{1}$$

Page 5: In the text line between equations (5) and (6), delete the word "finite".

Page 7: Change equations (8) and (9) to:

$$E_{TOT} = n\,(1 - R_n) \quad . \tag{8}$$

$$E_B = 1 - R_n \quad . \tag{9}$$

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16. ABSTRACT

The Laser Beam Manifold is a new device for transforming a single, narrow, collimated beam of light into several beams of desired intensity ratios; e.g., all of the outgoing beams might be of the same intensity. The Laser Beam Manifold's function is similar to that of a beam splitter, but the Laser Beam Manifold divides the beam into several rather than only two beams. The device consists of a single optical substrate with a metallic coating on both optical surfaces. By changing the entry point, the number of outgoing beams can be varied.

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INTRODUCTION

The Laser Beam Manifold (LBM) is a device for transforming a single, narrow, collimated beam of light into a series of n, approximately equally intense, beams. The LBM has many potential uses in the areas of optics, photogrammetry, security systems, and particle or velocity measurements where spatial resolution is important. General optical utilization of the LBM would be necessary for applications requiring three or more beams from a single source. An LBM can be utilized to provide a photographable grid within a test section for photogrammetric studies. The LBM may have some application in security systems where each of a series of beams (IR) activates an alarm when interrupted. In fluid velocity studies the Laser Doppler Velocimeter (LDV) has proved popular in recent years. One drawback is that commercially available models only measure velocities at a single point at a given instant. By employing LBM's, velocities at several points could be measured simultaneously. Aerosol size and number measurements sometimes involve passing a laser beam through the aerosol and measuring scattering intensities. In some instances measurement of size and number information at several locations simultaneously is desirable. Use of the LBM could significantly simplify required measurement apparatus.

An LBM is an uncomplicated device which can be manufactured at low cost in any laboratory with vacuum evaporation apparatus. It consists of an optical substrate with a fully reflecting rear surface and partially reflecting front surface. The reflectance on the front surface is varied by varying the reflective film thickness across the substrate. In theory the emerging beams can be made exactly uniform or in any intensity ratio desired. A grid looking very much like graph paper with emphasized lines and less intense lines could be created.

While Laser Beam Manifold is the name of the device, collimated light beams could be utilized with an LBM. In some cases where color dispersion would be a problem, a filtered source would be necessary. Using gaseous emission sources and thick, high-dispersion substrates, arrays of colored lines in regular sequences might be possible. Some lasers can lase at several lines simultaneously, providing a high-quality collimated, gaseous emission source.

The prototype model described in this report works in a transmission mode emitting parallel beams which are equally spaced. In some instances equally spaced beams might not be desirable. Unequally spaced beams could be achieved by coating the sides of a wedge or prism. Other geometrically complex substrates could be coated to obtain an unending variety of results.

The following discussion will present necessary equations for designing an LBM based on an optical flat type substrate. The results are theoretical, and certain data, such as film reflectance versus thickness with angle of incidence as a parameter, are not currently available in the literature. Practical considerations such as transmittance of the substrate will be considered. Available information that can be handled theoretically and is available will be examined.

FLAT SUBSTRATE LASER BEAM MANIFOLD CONCEPT

The basic LBM concept is illustrated in Figure 1. The incoming beam passes from the back to the front of the substrate. A part of the beam is transmitted through the front surface coating, and a part is reflected to the rear surface. The rear surface is as totally reflecting as possible. The process is repeated, with the result that a series of beams exist from the front surface of the manifold. The reflectance of the front surface is varied in such a manner that the exiting beams are of uniform intensity or that the intensity varies in a desired fashion. The spacings of the outgoing beams are related to the substrate thickness, d; index of refraction, n; and angle of incidence, θ_i, of the incoming beam by

$$S = \frac{2d \sin \theta_i \cos \theta_i}{\sqrt{n^2 - \sin^2 \theta_i}} \tag{1}$$

Assuming no absorption in the glass nor by the coatings, the following recursion relation in applicable:

$$R_{i+1} = \frac{1}{2 - R_i} \tag{2}$$

where R_i is the reflectance of the beam at the (n-i)th reflection point of the front surface. n is the total number of desired beams. The solution of equation (2) with initial condition $R_1 = 0$ is

$$R_i = \frac{i-1}{i} \quad . \tag{3}$$

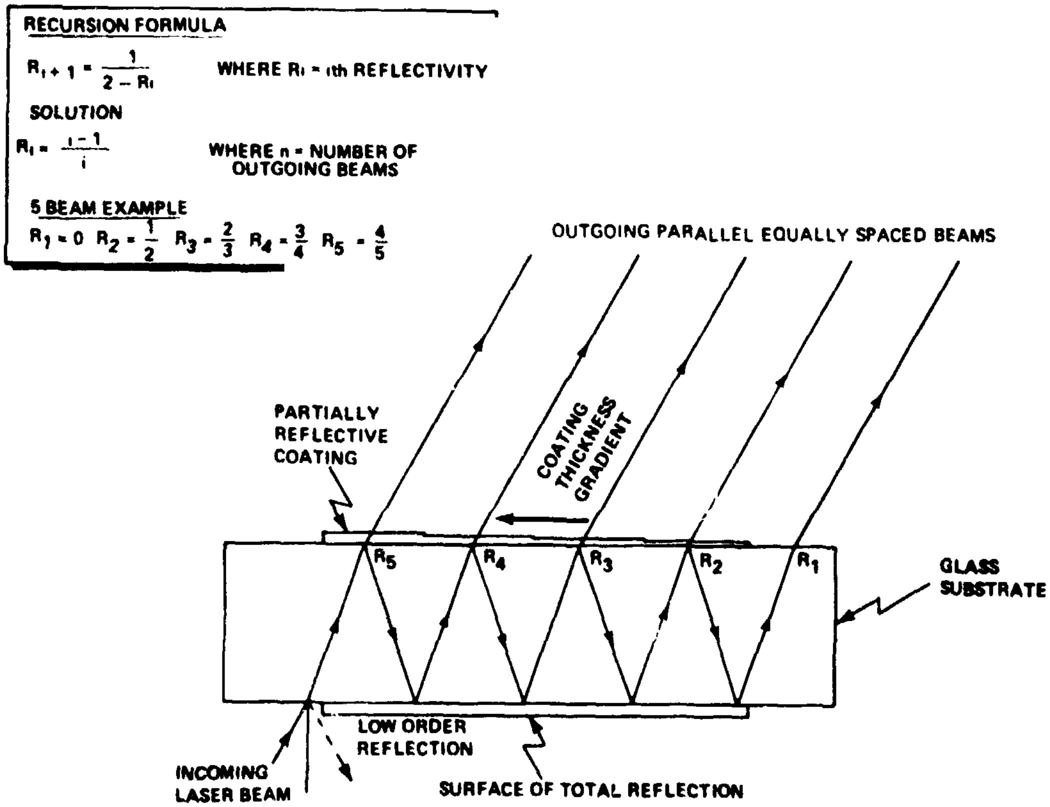

Figure 1. Laser beam manifold concept.

From equation (2) a series of three beams have reflectances $R_1 = 0$, $R_2 = 1/2$, and $R_3 = 2/3$. Four beams have reflectances $R_1 = 0$, $R_2 = 1/2$, $R_3 = 2/3$, and $R_4 = 3/4$. The sequences continue in this manner. This result is not exactly accurate even for the ideally transparent substrate with nonabsorptive coatings. The reason is that the last reflectance can never be zero. Even at normal incidence, an optical glass will reflect 4 percent of an incident beam. The nonzero value of the final reflectance can be taken into account in a straightforward manner by simply changing the initial condition, R_1. The solution to equation (2) for the new initial condition is

$$R_i = \frac{(i-1) - (i-2)\, R_1}{i - (i-1)\, R_1} \; . \tag{4}$$

Note that R_1 is actually the final reflectance at the point the last beam leaves the substrate rather than the first reflectance, as the subscript would seem to imply.

The nature of the preceding initial value problem provides a basis for implementation of an LBM. Any LBM with n beams has the same series of reflectances R_1 to R_n as an LBM with n + 1 reflectances. R_{n+1} is the only difference in the two series. Hence an LBM can be constructed with coating for the largest number of beams that would ever be necessary for a given application. By making the incident beam enter the substrate at different points, as many (up to n) or as few beams as desired can be developed. A detailed drawing is shown in Figure 2. The rear surface is depicted half totally reflecting and half clear. The clear half allows the raw beam to enter at the desired location. A beam entering the LBM of Figure 2 near the top of the triangle of clear surface will result in a maximum number of exiting beams. By moving the entering beam to the upper left along the line of demarcation, as shown, more exit beams are created. Conversely, moving to the lower right results in fewer beams.

Equation (3) accounts for the final reflectance, R_1, but does not include absorption effects within the optical substrate and at the metallic film surfaces These effects if assumed uniform across the face of the substrate can be

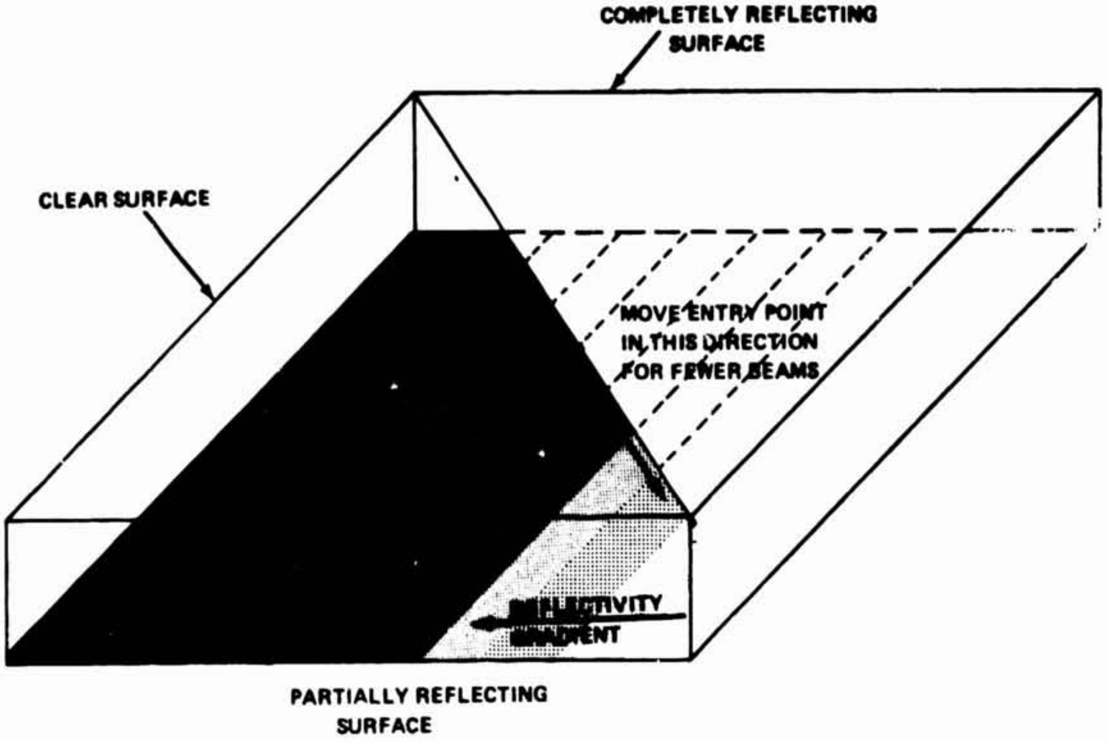

Figure 2. Possible LBM construction.

accounted for in the single parameter t, which is the transmittance from beam reflection to beam transmission ($t = 1 - \alpha$ where α is the absorption coefficient). The resulting recursion equation is

$$R_{i+1} = \frac{1}{1 + (1-R_i)\, t} \quad . \tag{5}$$

Again, this nonlinear finite difference equation can be solved with the result

$$R_i = \frac{1 - R_1 t - t^{i-1}(1-R_1)}{1 - R_1 t - t^{i}(1-R_1)} \quad . \tag{6}$$

The preceding results are for n equally intense exit beams. The results are entirely theoretical, and definition of t and R_i as a function of film thickness, angle of incidence, etc., is required. In the preceding analysis the assumption is made that t does not change from reflection to reflection. Since film thickness of one surface is a function of i, the assumption cannot be precisely true. Finally, to design the substrate, R_i at an interface must be a known function of film thickness, and angle of incidence. This detailed information is not currently available. For precision manufacturing this gap in knowledge should be filled.

The properties of finite difference equations play a role in design. Working backwards from the last reflectance, using R_1 as the initial condition, the first n reflectances of an n beam LBM are the same for an n beam LBM as for an n + 1, n + 2, or n + 100 beam LBM. Figure 3 is an example of the required reflectances. Because of the rapid asymptotic advance of reflectances toward unity, the manufacture of LBM's for n greater than 20 will be difficult. High n LBM manufacturing might be possible if feedback systems could monitor R_i during metallic film deposition.

Beams of uniform intensity may not be desirable. Beam intensity may be required in ratios $k_1:k_2:\ldots:k_n$. In this case the recursion relation is given by

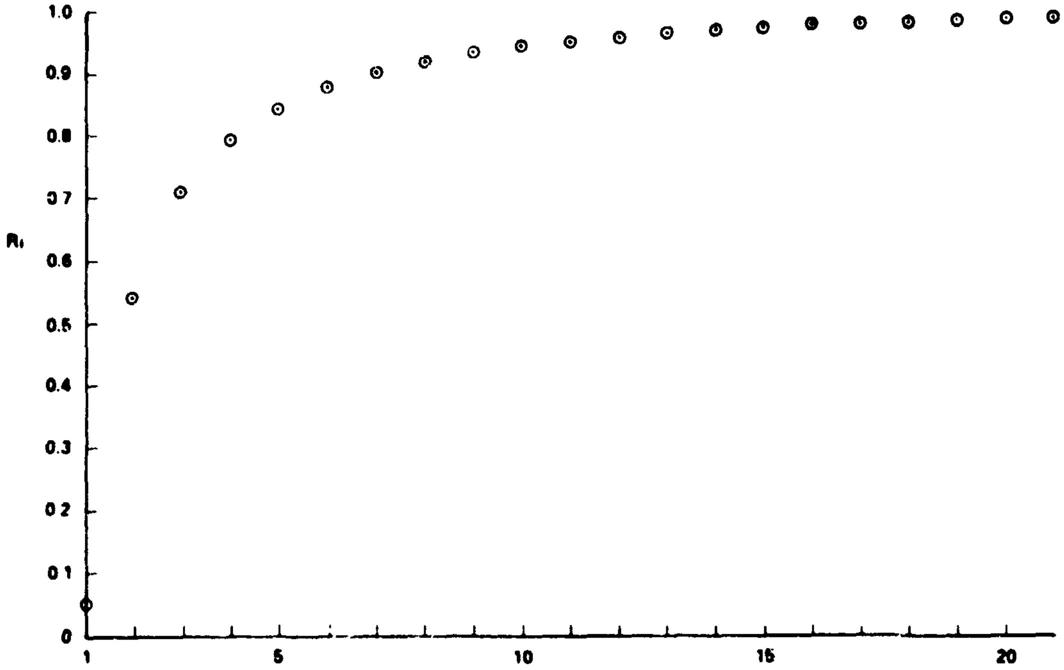

Figure 3. Sample reflectance for R_1 = 5 percent and t = 0.9.

$$R_{i+1} = \frac{1}{\frac{k_{i+1}}{k_i} t(1-R_i) + 1} \quad . \tag{7}$$

Note that in equation (7) the magnitudes of k_i and k_{i+1} are not important; only their ratio is of technical interest. Figure 4 illustrates equation (7) for various k values.

The longer the pathlength of the beam within the substrate, the less the energy in the n beams. Elementary considerations demonstrate that the fraction of the original beam intensity (just before the initial reflection) that is delivered to the n, equally intense, beams is given by

$$E_{TOT} = n(1 - R_{n-1}) \quad . \tag{8}$$

Figure 5 illustrates the total energy fraction.

By similar considerations the energy fraction in each beam is

$$E_B = 1 - R_{n-1} \quad . \tag{9}$$

Figure 6 illustrates equation (9).

Although calculation of theoretical reflectances is simple using a programmable calculator, the Appendix contains tables for uniform beam intensity for different values of R_1 and t.

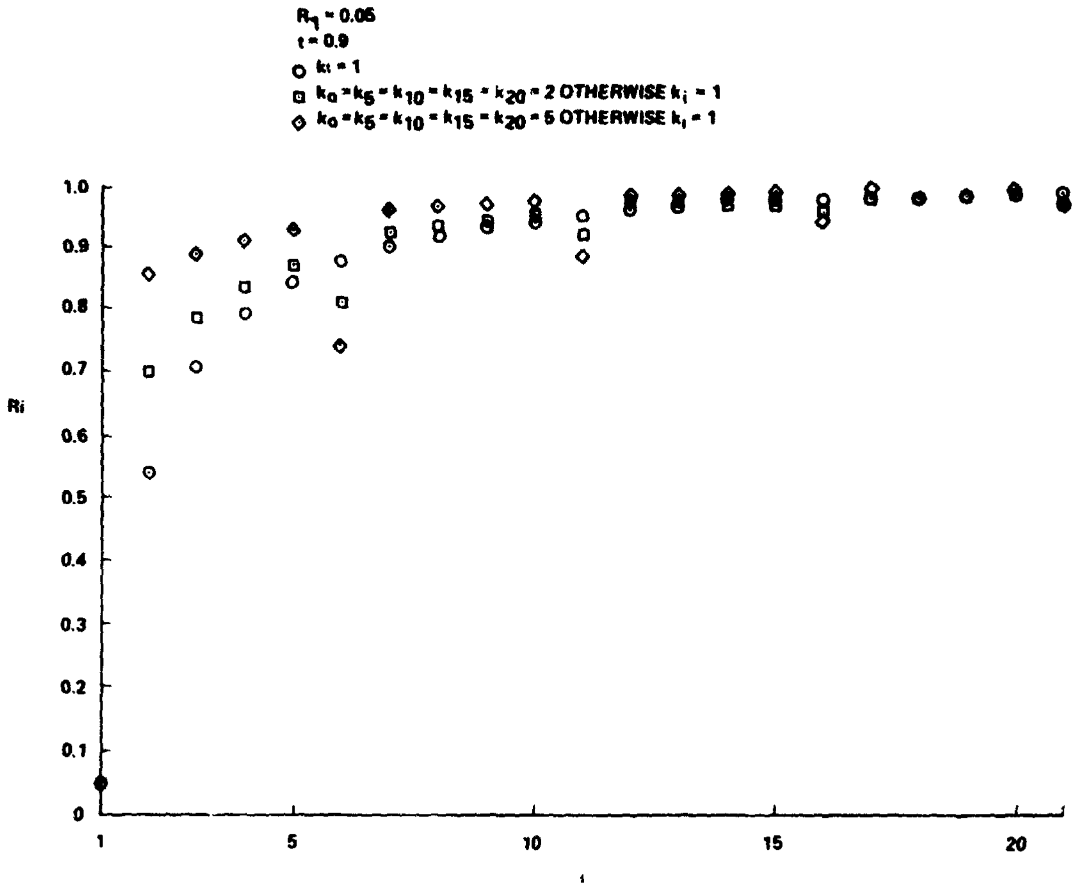

Figure 4. Reflectance functions for nonuniform beams.

CONCLUSIONS

The LBM has potential applications in many areas, including two-phase fluid flow measurement, aerosol sizing, security systems, laboratory photogrammetry, and general optics. An uncomplicated LBM can be easily fabricated in laboratories with vacuum evaporation apparatus.

The mathematics of construction was presented in terms of useful empirical parameters. LBM development into a precision optical element awaits the measurement of reflectances and absorptances as a function of angles of incidence. Useful prototypes can be constructed without precision reflectance and transmittance data.

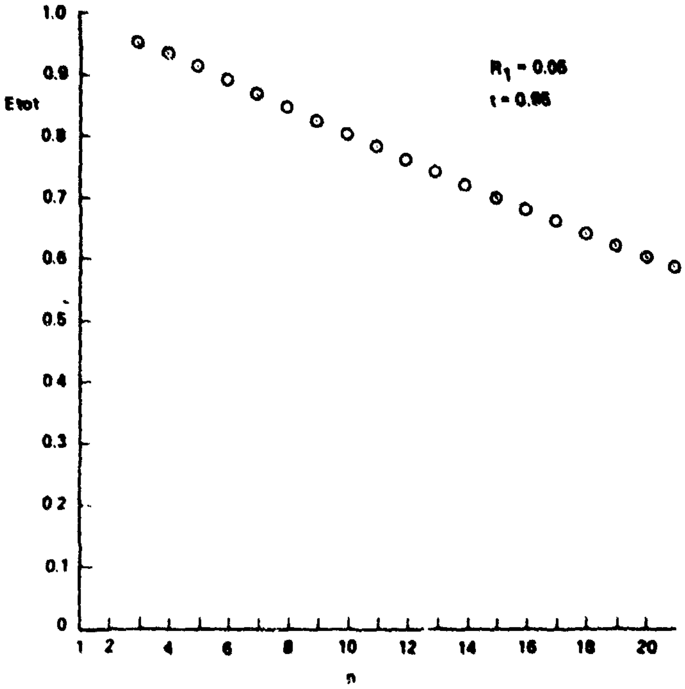

Figure 5. Total energy fraction emitted by n beams.

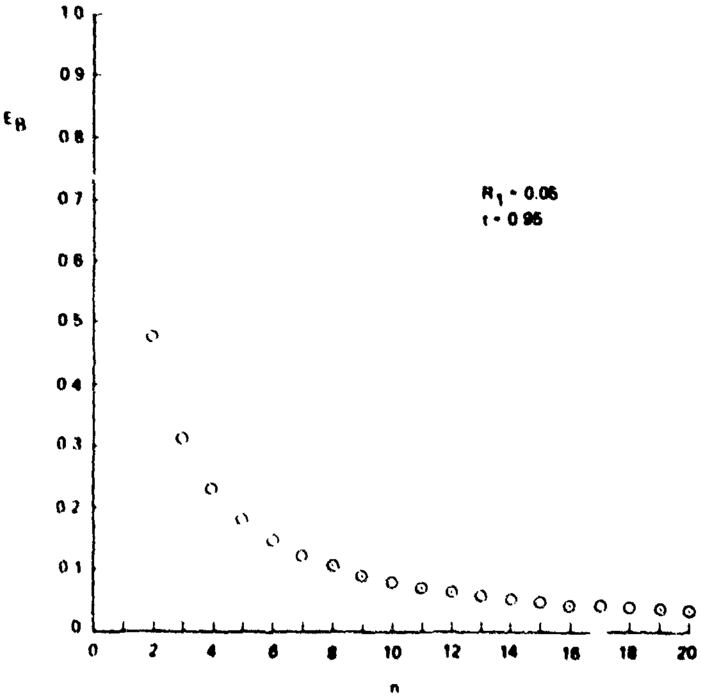

Figure 6. Energy contained in each of n beams.

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APPENDIX

THEORETICAL REFLECTANCES FOR VARIOUS VALUES OF SUBSTRATE TRANSMISSION, t AND INITIAL REFLECTANCE, R_1.

	t = 0.975				0.950			
n	R_1=0.05	0.1	0.2	0 5	0.05	0.1	0.2	0.5
1	0.050	0.100	0.200	0.500	0.05	0.100	0.200	0.500
2	0.519	0.533	0.562	0.672	0.526	0.539	0.568	0.678
3	0.681	0.687	0.701	0.758	0.689	0.695	0.709	0.766
4	0.763	0.766	0.774	0.809	0.772	0.776	0.783	0.818
5	0.812	0.814	0.819	0.843	0.822	0.824	0.829	0.853
6	0.845	0.847	0.850	0.867	0.855	0.857	0.861	0.877
7	0.869	0.870	0.873	0.885	0.879	0.880	0.883	0.895
8	0.887	0.887	0.890	0.899	0.897	0.898	0.900	0.910
9	0.900	0.901	0.903	0.911	0.911	0.912	0.913	0.921
10	0.912	0.912	0.913	0.920	0.922	0.923	0.924	0.930
11	0.921	0.921	0.922	0.928	0.931	0.931	0.933	0.938
12	0.928	0.929	0.929	0.934	0.938	0.939	0.940	0.944
13	0.935	0.935	0.936	0.940	0.945	0.945	0.946	0.950
14	0.940	0.940	0.941	0.944	0.950	0.950	0.951	0.954
15	0.945	0.945	0.946	0.949	0.955	0.955	0.956	0.958
16	0.949	0.949	0.950	0.952	0.959	0.959	0.960	0.962
17	0.953	0.953	0.953	0.956	0.962	0.963	0.963	0.965
18	0.956	0.956	0.956	0.958	0.965	0.966	0.966	0.968
19	0.959	0.959	0.959	0.961	0.968	0.968	0.969	0.970
20	0.961	0.961	0.962	0.963	0.971	0.971	0.971	0.973

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	t = 0.925				t = 0.900			
n	R_1=0.05	0.1	0.2	0.5	0.05	0.1	0.2	0.5
1	0.050	0.100	0.200	0.500	0.050	0.100	0.200	0.500
2	0.532	0.546	0.575	0.684	0.539	0.552	0.581	0.690
3	0.698	0.704	0.718	0.774	0.707	0.713	0.726	0.782
4	0.782	0.785	0.793	0.827	0.791	0.795	0.802	0.836
5	0.832	0.834	0.839	0.862	0.842	0.844	0.849	0.871
6	0.865	0.867	0.871	0.887	0.875	0.877	0.880	0.896
7	0.889	0.890	0.893	0.905	0.899	0.900	0.903	0.915
8	0.907	0.908	0.910	0.919	0.917	0.918	0.920	0.929
9	0.921	0.922	0.923	0.931	0.930	0.931	0.932	0.940
10	0.932	0.932	0.934	0.940	0.941	0.942	0.943	0.948
11	0.941	0.941	0.942	0.947	0.951	0.950	0.951	0.956
12	0.948	0.948	0.949	0.953	0.957	0.957	0.958	0.962
13	0.954	0.954	0.955	0.959	0.962	0.963	0.963	0.967
14	0.959	0.960	0.960	0.963	0.967	0.968	0.968	0.971
15	0.964	0.964	0.964	0.967	0.971	0.972	0.972	0.974
16	0.968	0.968	0.968	0.970	0.975	0.975	0.975	0.977
17	0.971	0.971	0.971	0.973	0.978	0.978	0.978	0.980
18	0.974	0.974	0.974	0.976	0.980	0.981	0.981	0.982
19	0.976	0.976	0.977	0.978	0.983	0.983	0.983	0.984
20	0.979	0.979	0.979	0.980	0.985	0.985	0.985	0.986

APPROVAL

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By Warren Campbell and Robert B. Owen

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

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