NASA Technical Memorandum 4077

A Method for Monitoring the Variability in Nuclear Absorption Characteristics of Aviation Fuels

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A Method for Monitoring the Variability in Nuclear Absorption Characteristics of Aviation Fuels

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Abstract

A technique for monitoring variability in the nuclear absorption characteristics of aviation fuels has been developed. It is based on a highly collimated low energy gamma radiation source and a sodium iodide counter. The source and the counter assembly are separated by a geometrically well-defined test fuel cell. A computer program for determining the mass attenuation coefficient of the test fuel sample, based on the data acquired for a preset counting period, has been developed and tested on several types of aviation fuel.

Introduction

We have recently demonstrated (ref. 1) the feasibility of a nuclear gauging system for fuel quantity measurement onboard an aircraft. It is based on monitoring the number of photons arriving at a counting station located a predetermined distance from an Am^{241} source capsule. Several such source capsule-counting station assemblies are judiciously located throughout the fuel tanks. When the entire pathlength between the source capsule and the counter station is occupied by the fuel, the number of surviving photons will be minimal. If, on the other hand, there is no fuel in the photon path, the number of surviving photons will be maximum. By combining the information about the counting rates and the geometrical locations of the source-counter assemblies in the tanks, a reliable measure of the total fuel content of the tank can be obtained at any time. This, of course, is true only if the quality of the fuel remains constant. Recently, the Airlines Electronic Engineering Committee (AEEC) has reported concern about the variability of aviation fuel characteristics as a function of the season and geographical origin (refs. 2, 3, and 4). The concern arises from variations in the fuel composition as well as the nature and amount of contaminants. In an effort to identify the degree of variability in fuel quality, we have set up a fuel characteristics monitoring system. This system and the computational procedure used to measure changes in the nuclear absorption coefficients of the fuel samples are described in this report.

Fuel Characteristics Monitoring System

The fuel characteristics monitoring system is made up of a highly collimated 10 μCi Am^{241} (59.5 keV) gamma radiation source and a 2-in-diameter × 2-in. NaI(Tl) crystal mounted on a photomultiplier. The source and the counter assembly are separated by a 2-in-diameter × 4-in. glass fuel cell. The number of photons arriving at the NaI(Tl) crystal depends on the quality of the fuel in the fuel cell.

$$I_x = I_o e^{-\mu x} + B$$

where

I_x number of photons arriving at the NaI (Tl) crystal

I_o number of photons incident on the fuel cell

μ linear attenuation coefficient of the fuel

x fuel path length (fuel cell length)

B background count (counts recorded in the absence of the source)

By using a well-characterized medium in the fuel cell—such as air or distilled water—the value of I_o can be determined from a measured value of I_x. Once I_o is determined for a fixed source-detector assembly, I_x becomes the critical measurable parameter in the fuel quality study. An independent measurement of the density of the test fuel, coupled with a value of linear attenuation coefficient determined from the preceding equation, then permits a direct computation of mass attenuation coefficient (μ/ρ, cm^2/g) of the sample (where ρ is the density of the test fluid).

Computational Procedure

Basic description. A computer program for gamma radiation mass attenuation coefficient (PGRMAC) has been written in MS-FORTRAN 77 Version 3.31 for personal computers with a fixed-disk system, using MS-DOS Version 3.3. The program requires 12 156 bytes of disk space for storage.

The program models the experimental procedure for calculating gamma ray attenuation coefficients in the test medium. The geometrical details of the test system are summarized in figure 1. Figure 2 is a photograph of the experimental system. As shown in figure 1, gamma rays have to pass through air, glass fuel cell walls, the test fluid, and a thin aluminum housing to reach the detector surface. The intensity (number of photons) of gamma radiation arriving at the detector can be written as follows:

$$I_x = I_o\left(e^{-\mu_{\text{air}} x_{\text{air1}}} e^{-\mu_{\text{glass}} x_{\text{glass}}} \times e^{-\mu_{\text{fluid}} x_{\text{fluid}}} e^{-\mu_{\text{al}} x_{\text{al}}}\right) + B \qquad (1)$$

where

I_x intensity of gamma radiation arriving at the detector

I_o intensity of gamma radiation incident on fuel cell

μ_{air}	linear attenuation coefficient for air
μ_{glass}	linear attenuation coefficient for glass
μ_{al}	linear attenuation coefficient for aluminum
μ_{fluid}	linear attenuation coefficient for the test fluid
x_{air1}	air path length
x_{glass}	glass path length
x_{al}	aluminum path length
x_{fluid}	fluid path length
B	background count (counts recorded in the absence of the source)

In equation (1), μ_{air}, x_{air1}, μ_{glass}, x_{glass}, μ_{al}, x_{al}, and x_{fluid} are known parameters (refs. 1, 5, 6, and 7). The intensities I_o and I_x need to be calculated or measured. To determine I_o, we can choose air as the reference medium. Equation (1), after subtracting the background count, can be written as follows:

$$I_x - B = I_o\left(e^{-\mu_{air}x_{air1}} e^{-\mu_{glass}x_{glass}} \times e^{-\mu_{fluid}x_{fluid}} e^{-\mu_{al}x_{al}}\right)$$

$$I_{x(air)} = I_o\left(e^{-\mu_{air}x_{air1}} e^{-\mu_{glass}x_{glass}} \times e^{-\mu_{air}x_{fluid(air)}} e^{-\mu_{al}x_{al}}\right) \qquad (2)$$

This gives the following relation for I_o:

$$I_o = I_x(\text{air}) \exp\left\{\mu_{air}\left[x_{air1} + x_{fluid(air)}\right] + \mu_{glass}x_{glass} + \mu_{al}x_{al}\right\} \qquad (3)$$

$$I_o = I_x(\text{air}) \exp\left(\mu_{air}x_{air2} + \mu_{glass}x_{glass} + \mu_{al}x_{al}\right) \qquad (4)$$

where

$$x_{air2} = x_{air1} + x_{fluid(air)}$$

Since I_x(air) can be determined experimentally, I_o is readily calculated from equation (4).

Once I_o has been obtained from equation (4), the program proceeds to compute the linear attenuation coefficient of the test fluid from equation (1). When the glass cell is filled with the test fluid, equation (1) can be written as

$$I_x = I_o \exp\left(-\mu_{air}x_{air1} - \mu_{glass}x_{glass} - \mu_{fluid}x_{fluid} - \mu_{al}x_{al}\right) \qquad (5)$$

Then

$$\mu_{fluid} = \left[\ln(I_o/I_x) - \mu_{air}x_{air1} - \mu_{glass}x_{glass} - \mu_{al}x_{al}\right]/x_{fluid} \qquad (6)$$

The calculated value from equation (6) is the linear attenuation coefficient of the test fluid. Since the mass attenuation coefficient of the medium is of more fundamental importance than the linear attenuation coefficient, the density of the test fluid should be determined beforehand independently. In this program, the density of the test medium, measured experimentally, is read as an input value, and the mass attenuation coefficient is simply equal to the linear attenuation coefficient divided by the density, i.e.,

$$(\mu)_{mass} = \frac{(\mu)_{linear}}{\text{Density}} \qquad (7)$$

The region of the gamma ray spectrum in which we are interested is selected, and it is marked as the region of interest (ROI) in figure 3. This includes most of the area under the total capture peak in the spectrum. The energy distribution of the gamma source forms a peak in the ROI, and the area under the peak in the ROI is interpreted as I_n for each medium in the program. The background counts within the ROI have to be determined and then subtracted from the full spectral counts in the ROI before it can be used to determine I_x or I_o. The ROI in this program is selected to be from channel 241 to channel 421. The peak falls at the middle of the region, as seen in figure 3; this range is quite adequate to monitor and analyze the characteristics of each test fluid.

Program input, output, and usage. The program input is made of two parts containing several parameters and related file names. The first part of the input consists of 10 essential parameters that are assigned as constants in the program. They are listed below:

MUAIR=0.0002132	XGLS=0.680
MUGLS=0.46654	XAL=0.079
MUAL=0.6639	XFUEL=10.062
XAIR1=5.080	LBEG=241
XAIR2=XAIR1 + XFLUID(AIR)	LEND=421

In the list above, MUAIR, MUGLS, and MUAL are the linear attenuation coefficients of air, glass, and aluminum, respectively (refs. 5, 6, and 7); XAIR, XGLS, XAL, and XFUEL are the air, glass, aluminum, and test medium pathlengths, respectively. The parameters LBEG and LEND correspond to the beginning and ending channel numbers for the ROI. The second part of the input is an eight-character string, which is read interactively from the keyboard, and which corresponds to two binary file names and one specific record in a data base. These two binary files, which are generated from the multichannel analyzer (MCA), refer to the gamma spectra through air and the test fluid taken on the same day. Each record in the data base has nine terms of information: density, temperature, type of medium, etc., in it.

The program generates four formatted output files. Two of them are data files, converted from the binary spectra through air and the test medium, that list channel numbers and counts in each of them as shown in tables I(a) and (b). Plots of the data in tables I(a) and (b) are shown in figures 4 and 5, respectively. From the data file of the air spectrum, the program calculates the value of I_o and determines the location of the centroid of the peak channel, MAXAIR, for air on that day. The program then computes I_x from the converted data file of the test fluid and determines the location of the peak centroid, MAXFLUID.

MAXAIR and MAXFLUID should coincide and should remain constant as long as the electronic system gain remains unchanged. Thus a determination of $\frac{\text{MAXAIR}}{\text{MAXFLUID}}$ serves as a system calibration check. Once I_o and I_x have been determined by the above procedure, the linear attenuation coefficient of the test fluid (MUFLUID) can be obtained from equation (6). Subsequently, the mass attenuation coefficient (ATCFM) is readily calculable. The other two output files, the printout and monitor display, provide a record of the desired information about the test medium.

Program flowchart and listings. The program flowchart and listings are summarized in appendices A and B, respectively.

Test of the Sensitivity of the System

To test the sensitivity of the monitoring system, mass attenuation coefficient measurements were made in common salt solutions in water containing different amounts of salt. The experimental results, along with the corresponding calculated values, are summarized in table II and illustrated in figure 6. It is apparent from the data shown in this table that the measured and calculated values of the mass attenuation coefficients for different solutions agree within ±0.5 percent.

Applications

The program PGRMAC has been applied to the measurement of mass attenuation coefficients for several types of aviation fuel. These fuels have been investigated previously and can thus provide a good test of the validity of the computational procedure. Results for JP-4, JP-5, and Jet A are summarized in tables III(a), (b), and (c), respectively.

The results for the three types of fuel are further consolidated in table IV.

Concluding Remarks

A simple technique for monitoring nuclear absorption characteristics of aviation fuels, based on low energy gamma ray attenuation in the test fuels, has been developed. It has been tested on three types of aviation fuels. It is noted that the mass attenuation coefficients of the three fuels are almost equal, even though their linear attenuation coefficients and densities are slightly different. It would therefore appear that a simultaneous measurement of linear and mass attenuation coefficients and densities is a highly informative procedure. It is further noted that the values of mass attenuation coefficients calculated by using the present procedure agree with the previously reported values to within ±1 percent. It is therefore concluded that the procedures developed here are quite adequate for monitoring variability of ≥0.5 percent in fuel absorption characteristics as a function of the season and geographical points of origin of the fuels.

The international aviation consortium has agreed to provide us fuel samples from various parts of the world over the next 12 months. The linear and mass attenuation coefficients for 59.5 keV Am^{241} gamma rays, as well as densities of the fuel samples, will be measured to assess the fuel composition variability.

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Table I. Summary of Gamma Ray Spectrum

(a) Through air

Channel number	Counts	Channel number	Counts	Channel number	Counts	Channel number	Counts
1	0	56	6	111	24	166	195
2	0	57	7	112	19	167	176
3	0	58	11	113	30	168	169
4	0	59	9	114	12	169	178
5	0	60	6	115	19	170	163
6	0	61	5	116	19	171	175
7	0	62	2	117	30	172	155
8	0	63	4	118	34	173	157
9	0	64	7	119	25	174	171
10	0	65	9	120	32	175	182
11	0	66	7	121	43	176	173
12	0	67	5	122	34	177	164
13	0	68	6	123	45	178	181
14	0	69	0	124	27	179	140
15	0	70	0	125	30	180	155
16	0	71	3	126	56	181	151
17	0	72	9	127	40	182	153
18	0	73	11	128	44	183	128
19	0	74	0	129	39	184	147
20	0	75	8	130	50	185	122
21	0	76	2	131	61	186	141
22	0	77	1	132	61	187	121
23	0	78	0	133	78	188	113
24	0	79	1	134	72	189	110
25	0	80	6	135	80	190	93
26	0	81	1	136	80	191	99
27	0	82	15	137	61	192	89
28	0	83	5	138	72	193	104
29	0	84	5	139	92	194	81
30	0	85	9	140	86	195	74
31	0	86	15	141	101	196	87
32	0	87	0	142	89	197	55
33	0	88	8	143	125	198	71
34	0	89	1	144	120	199	54
35	0	90	0	145	132	200	57
36	0	91	2	146	109	201	58
37	0	92	7	147	105	202	39
38	0	93	4	148	123	203	51
39	0	94	15	149	127	204	36
40	0	95	1	150	144	205	24
41	0	96	10	151	134	206	34
42	5	97	11	152	140	207	39
43	2	98	8	153	114	208	32
44	0	99	23	154	142	209	14
45	0	100	12	155	160	210	28
46	14	101	16	156	133	211	16
47	0	102	8	157	142	212	9
48	1	103	13	158	149	213	41
49	10	104	21	159	186	214	24
50	0	105	10	160	151	215	18
51	4	106	12	161	163	216	16
52	3	107	12	162	172	217	17
53	9	108	10	163	165	218	13
54	6	109	11	164	168	219	13
55	5	110	16	165	162	220	16

Table I. Continued

(a) Concluded

Channel number	Counts	Channel number	Counts	Channel number	Counts	Channel number	Counts
221	10	276	123	331	1082	386	101
222	17	277	140	332	1067	387	97
223	13	278	165	333	1039	388	107
224	18	279	176	334	1032	389	111
225	19	280	214	335	1032	390	105
226	13	281	191	336	1017	391	76
227	1	282	227	337	1035	392	62
228	3	283	232	338	939	393	56
229	12	284	247	339	992	394	45
230	9	285	231	340	969	395	61
231	4	286	264	341	973	396	60
232	7	287	301	342	949	397	43
233	3	288	315	343	967	398	52
234	8	289	307	344	963	399	26
235	0	290	373	345	919	400	45
236	21	291	384	346	922	401	34
237	11	292	359	347	845	402	13
238	23	293	395	348	866	403	13
239	22	294	424	349	823	404	16
240	22	295	424	350	775	405	55
241	20	296	481	351	719	406	0
242	20	297	468	352	721	407	4
243	14	298	512	353	728	408	22
244	16	299	506	354	701	409	16
245	12	300	526	355	672	410	5
246	26	301	581	356	672	411	30
247	27	302	580	357	638	412	0
248	20	303	622	358	571	413	1
249	13	304	643	359	563	414	12
250	24	305	720	360	595	415	0
251	38	306	702	361	515	416	15
252	24	307	713	362	527	417	0
253	24	308	787	363	469	418	4
254	24	309	816	364	458	419	0
255	22	310	799	365	408	420	0
256	28	311	818	366	398	421	0
257	31	312	851	367	398	422	0
258	48	313	847	368	324	423	9
259	37	314	866	369	364	424	7
260	68	315	919	370	364	425	7
261	57	316	897	371	344	426	16
262	40	317	961	372	294	427	0
263	39	318	960	373	287	428	0
264	73	319	949	374	289	429	6
265	70	320	1036	375	259	430	0
266	83	321	976	376	256	431	8
267	86	322	1010	377	223	432	0
268	108	323	976	378	195	433	14
269	83	324	1034	379	205	434	0
270	106	325	1085	380	172	435	13
271	92	326	1019	381	184	436	0
272	96	327	1034	382	145	437	0
273	120	328	1050	383	133	438	0
274	112	329	1056	384	125	439	7
275	147	330	1049	385	119	440	0

Table I. Continued

(b) Through fuel (Jet A)

Channel number	Counts	Channel number	Counts	Channel number	Counts	Channel number	Counts
1	0	56	11	111	163	166	19
2	0	57	3	112	172	167	38
3	0	58	5	113	165	168	42
4	0	59	10	114	168	169	40
5	0	60	5	115	162	170	53
6	0	61	0	116	195	171	27
7	0	62	4	117	176	172	32
8	0	63	1	118	169	173	43
9	0	64	3	119	178	174	38
10	0	65	0	120	163	175	35
11	0	66	8	121	175	176	30
12	0	67	10	122	155	177	38
13	0	68	2	123	157	178	29
14	0	69	6	124	171	179	51
15	0	70	4	125	182	180	26
16	0	71	0	126	173	181	37
17	0	72	0	127	164	182	32
18	0	73	4	128	181	183	30
19	0	74	0	129	140	184	36
20	0	75	6	130	155	185	34
21	0	76	4	131	151	186	29
22	0	77	3	132	153	187	23
23	0	78	5	133	128	188	29
24	0	79	8	134	147	189	33
25	0	80	6	135	122	190	24
26	0	81	0	136	141	191	10
27	0	82	6	137	121	192	33
28	0	83	9	138	113	193	19
29	0	84	2	139	110	194	22
30	0	85	4	140	93	195	8
31	0	86	4	141	99	196	20
32	0	87	1	142	89	197	14
33	0	88	3	143	104	198	27
34	0	89	8	144	81	199	7
35	0	90	10	145	74	200	12
36	0	91	0	146	87	201	14
37	0	92	0	147	55	202	6
38	0	93	0	148	71	203	15
39	0	94	0	149	54	204	22
40	0	95	5	150	57	205	0
41	0	96	0	151	33	206	8
42	0	97	0	152	22	207	11
43	0	98	0	153	46	208	7
44	2	99	13	154	30	209	15
45	0	100	0	155	36	210	18
46	5	101	134	156	35	211	16
47	2	102	140	157	25	212	9
48	1	103	114	158	29	213	3
49	3	104	142	159	33	214	6
50	0	105	160	160	22	215	4
51	7	106	133	161	39	216	10
52	8	107	142	162	31	217	4
53	9	108	149	163	54	218	2
54	0	109	186	164	32	219	0
55	2	110	151	165	35	220	0

Table I. Concluded

(b) Concluded

Channel number	Counts	Channel number	Counts	Channel number	Counts	Channel number	Counts
221	2	276	50	331	251	386	13
222	7	277	28	332	255	387	27
223	11	278	43	333	219	388	6
224	0	279	54	334	214	389	18
225	5	280	44	335	238	390	18
226	1	281	58	336	235	391	13
227	13	282	44	337	240	392	5
228	6	283	58	338	234	393	6
229	0	284	53	339	188	394	28
230	6	285	54	340	235	395	20
231	8	286	83	341	218	396	19
232	11	287	64	342	228	397	22
233	12	288	57	343	181	398	6
234	15	289	71	344	213	399	8
235	2	290	105	345	180	400	12
236	0	291	83	346	171	401	3
237	5	292	91	347	211	402	2
238	9	293	82	348	184	403	1
239	10	294	103	349	178	404	0
240	8	295	98	350	194	405	0
241	12	296	94	351	169	406	0
242	9	297	104	352	170	407	3
243	1	298	128	353	178	408	2
244	0	299	150	354	109	409	16
245	8	300	126	355	169	410	3
246	8	301	130	356	129	411	0
247	14	302	113	357	143	412	5
248	0	303	134	358	117	413	16
249	7	304	141	359	120	414	0
250	18	305	166	360	106	415	0
251	19	306	152	361	116	416	2
252	10	307	158	362	113	417	0
253	17	308	181	363	113	418	0
254	10	309	173	364	117	419	4
255	15	310	197	365	66	420	2
256	12	311	187	366	89	421	0
257	9	312	174	367	75	422	0
258	10	313	189	368	84	423	0
259	7	314	184	369	57	424	1
260	3	315	194	370	61	425	5
261	25	316	209	371	76	426	0
262	14	317	224	372	71	427	4
263	13	318	227	373	70	428	0
264	9	319	208	374	49	429	0
265	18	320	234	375	54	430	3
266	3	321	198	376	44	431	11
267	17	322	242	377	50	432	6
268	15	323	246	378	32	433	8
269	8	324	244	379	26	434	0
270	23	325	234	380	33	435	0
271	25	326	244	381	30	436	0
272	19	327	232	382	33	437	17
273	25	328	243	383	27	438	3
274	33	329	225	384	0	439	11
275	32	330	259	385	20	440	7

Table II. Summary of Mass Attenuation Coefficients of Common Salt Solutions

Solution number	Salt solution composition	$\frac{\mu}{\rho}$(experimental), cm^2/g	$\frac{\mu}{\rho}$(calculated),* cm^2/g
1	100 percent saturated solution (35.14 g of salt per 100 cm^3 of H_2O)	0.2242 ± 0.0021	0.2243 ± 0.0013
2	80 percent saturated solution (28.11 g of salt per 100 cm^3 of H_2O)	0.2191 ± 0.0020	0.2189 ± 0.0014
3	60 percent saturated solution (21.08 g of salt per 100 cm^3 of H_2O)	0.2132 ± 0.0019	0.2128 ± 0.0015
4	40 percent saturated solution (14.06 g of salt per 100 cm^3 of H_2O)	0.2051 ± 0.0019	0.2061 ± 0.0016
5	20 percent saturated solution (7.03 g of salt per 100 cm^3 of H_2O)	0.1989 ± 0.0019	0.1985 ± 0.0019

* $\frac{\mu}{\rho}$(calculated) values were obtained as follows:

$$\left(\frac{\mu}{\rho}\right)_{\text{solution}} = W_1\left(\frac{\mu}{\rho}\right)_{\text{water}} + W_2\left(\frac{\mu}{\rho}\right)_{\text{common salt}}$$

where W_1 and W_2 are fractions of the solution by weight.

Table III. Summary of Results

(a) JP-4 fuel

File name	JN280261.CHN
Sample I.D.	026
Run number	1
Data collected at	09:12 on 27 June 88
Fuel type	JP-4
Source	NASA
Airline	I.R.D
Location	Langley
Delivery date	02-10-88
Peak centroid location (air)	Channel number 329.04
Peak centroid location (fuel)	Channel number 328.51
ROI	Channel number 241 to 421
Real time, sec	1800
Live time, sec	1797
I_o	102 744 ± 321
I_x	17 436 ± 132
Fuel temperature, °C	25.0
Fuel density, g/cm^3	0.7520
Linear attenuation coefficient, cm^{-1}	0.1392 ± 0.0015
Mass attenuation coefficient, cm^2/g	0.1851 ± 0.0020

(b) JP-5 fuel

File name	JN270251.CHN
Sample I.D.	025
Run number	1
Data collected at	11:04 on 26 June 88
Fuel type	JP-5
Source	NASA
Airline	I.R.D.
Location	Langley
Delivery date	02-10-88
Peak centroid location (air)	Channel number 330.01
Peak centroid location (fuel)	Channel number 329.21
ROI	Channel number 241 to 421
Real time, sec	1800
Live time, sec	1797
I_o	102 679 ± 320
I_x	15 756 ± 126
Fuel temperature, °C	25.0
Fuel density, g/cm^3	0.8086
Linear attenuation coefficient, cm^{-1}	0.1492 ± 0.0016
Mass attenuation coefficient, cm^2/g	0.1845 ± 0.0019

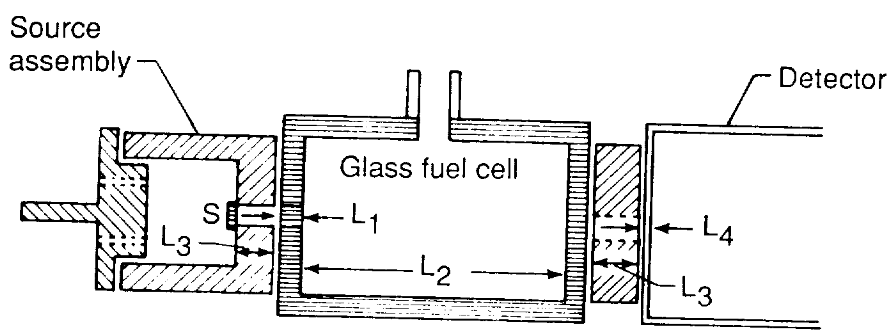
Table III. Concluded

(c) Jet A fuel

File name	JN270271.CHN
Sample I.D.	027
Run number	1
Data collected at	14:08 on 26 June 88
Fuel type	Jet A
Source	NASA
Airline	I.R.D.
Location	Langley
Delivery date	02-10-88
Peak centroid location (air)	Channel number 330.01
Peak centroid location (fuel)	Channel number 328.80
ROI	Channel number 241 to 421
Real time, sec	1800
Live time, sec	1797
I_o	102 679 ± 320
I_x	15 798 ± 126
Fuel temperature, °C	25.0
Fuel density, g/cm^3	0.8092
Linear attenuation coefficient, cm^{-1}	0.1490 ± 0.0016
Mass attenuation coefficient, cm^2/g	0.1841 ± 0.0019

Table IV. Summary of Attenuation Coefficients for Aviation Fuels Studied

Test fuel	Present study			Reported values (ref. 1)		
	Density, g/cm^3	Linear attenuation coefficient, cm^{-1}	Mass attenuation coefficient, cm^2/g	Density, g/cm^3	Linear attenuation coefficient, cm^{-1}	Mass attenuation coefficient, cm^2/g
JP-4	0.7520	0.1392 ± 0.0015	0.1851 ± 0.0020	0.7546	0.143 ± 0.003	0.190 ± 0.004
JP-5	0.8086	0.1492 ± 0.0015	0.1845 ± 0.0019	0.8097	0.150 ± 0.002	0.185 ± 0.003
Jet A	0.8092	0.1489 ± 0.0015	0.1841 ± 0.0019	0.8107	0.150 ± 0.002	0.185 ± 0.003



$x_{glass} = 2 \times L_1 = 0.680$ cm

$x_{fluid} = L_2 = 10.062$ cm

$L_3 = 2.540$ cm

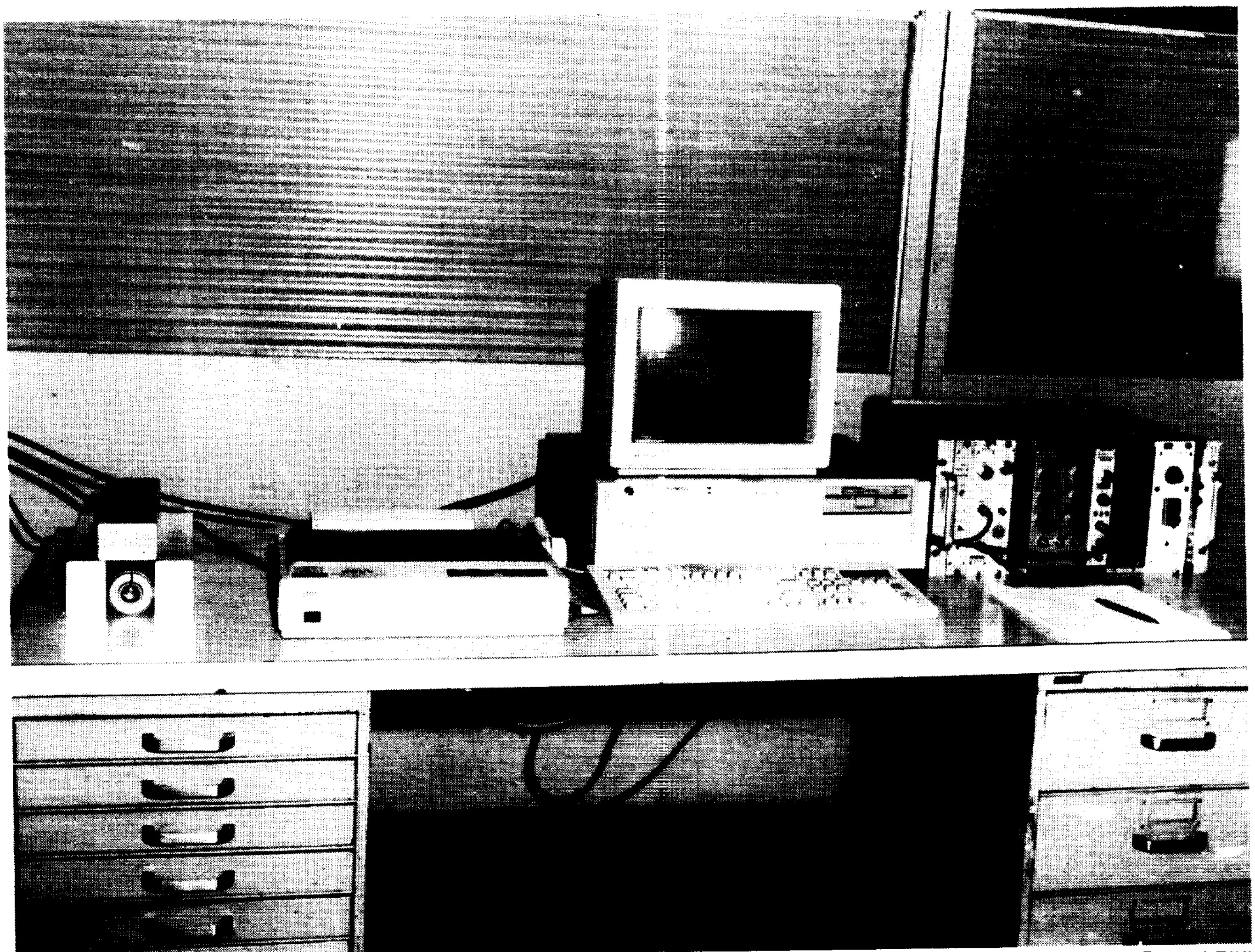
$x_{air1} = 2 \times L_3 = 5.080$ cm

$x_{al} = L_4 = 0.079$ cm

$x_{air2} = x_{fluid(air)} + x_{air1} = 15.142$ cm

S = americium 241 gamma source

Figure 1. Geometrical details of fuel cell and associated shields/collimators.



L-88-7755

Figure 2. Photograph of experimental system.

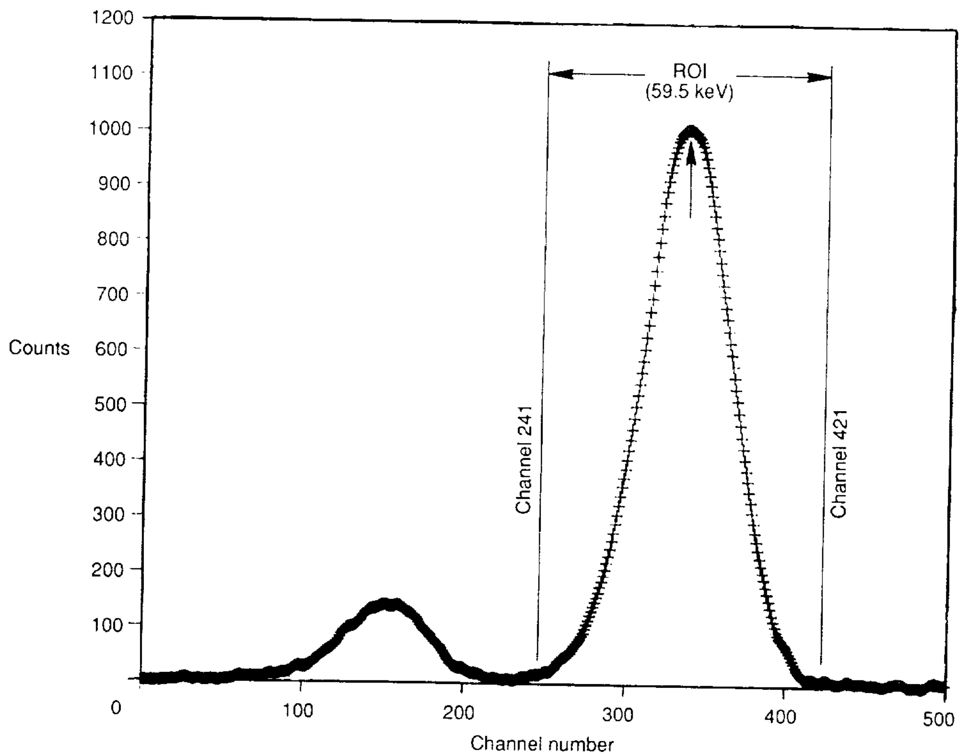


Figure 3. Gamma ray spectrum through air.

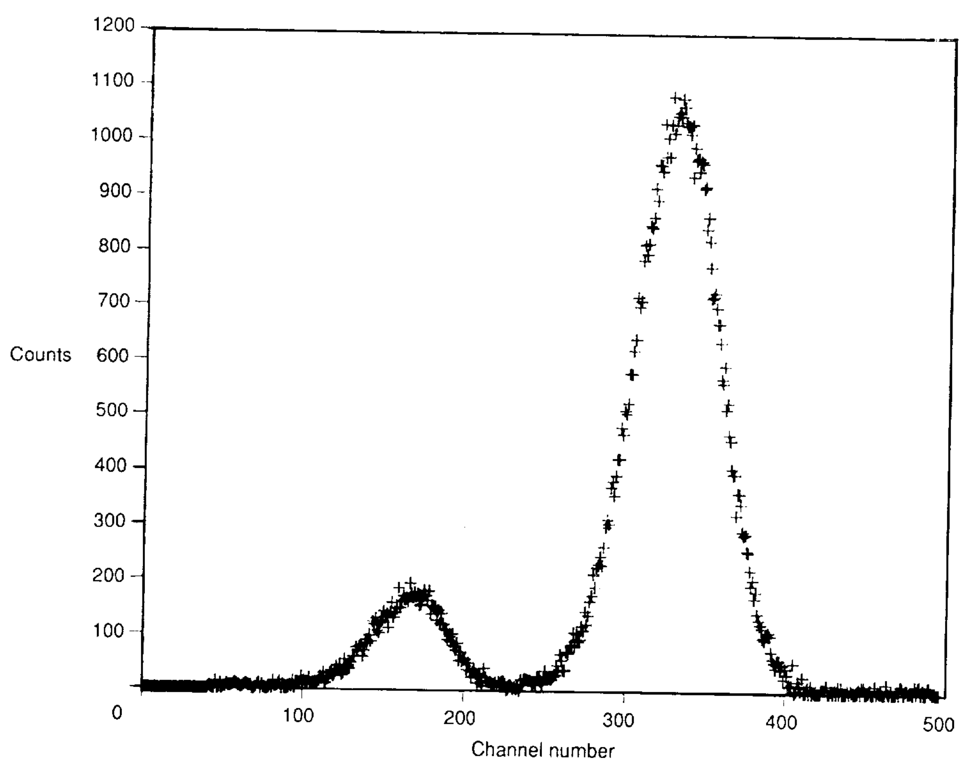


Figure 4. Spectrum of gamma rays transmitted through air.

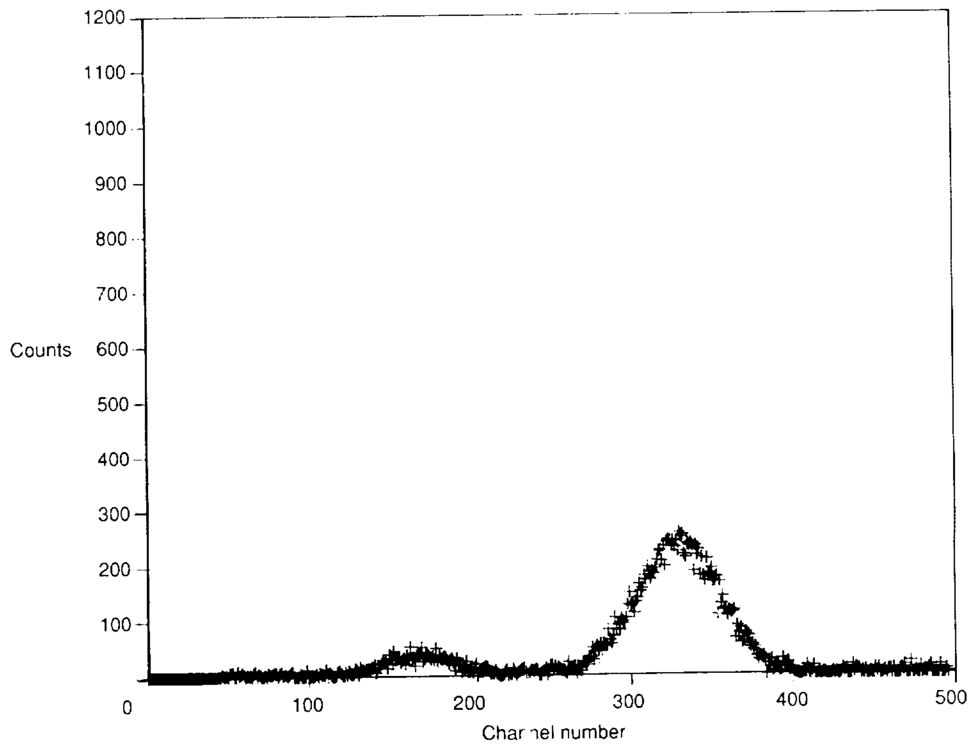


Figure 5. Spectrum of gamma rays transmitted through Jet A fuel.

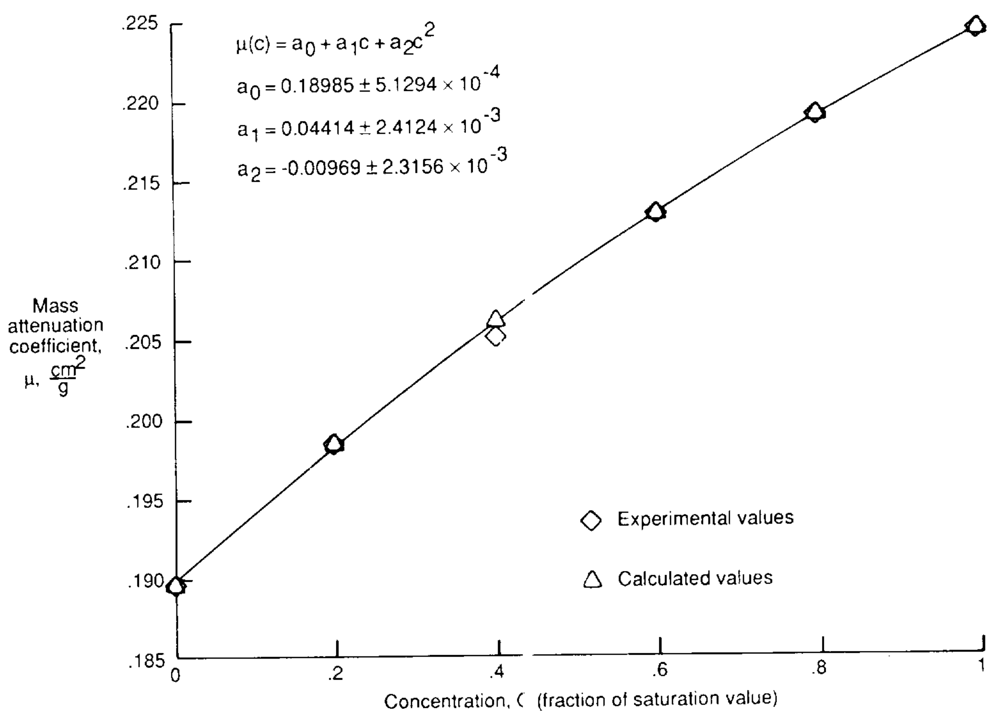
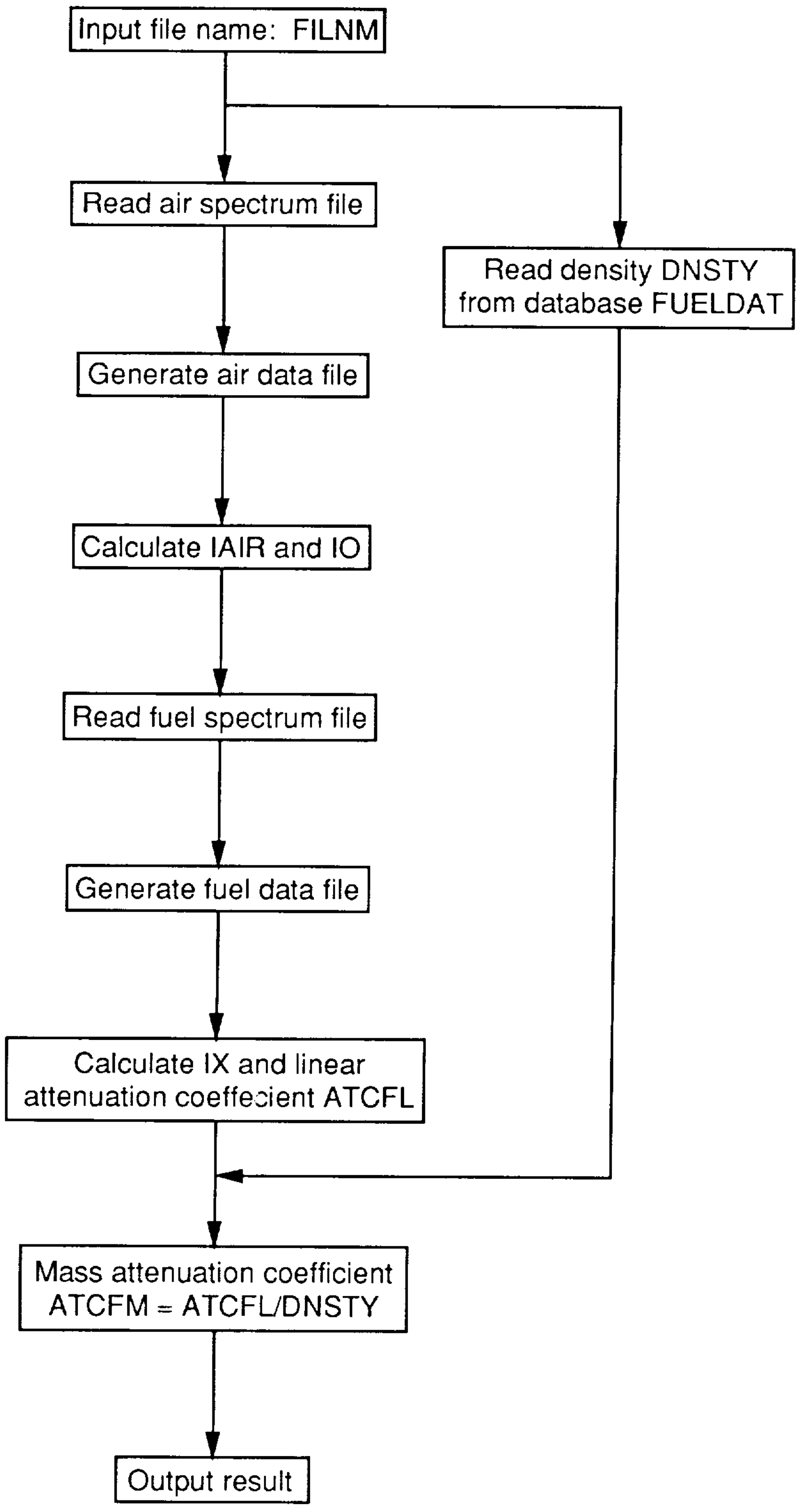


Figure 6. Experimental and calculated values of mass absorption coefficient of common salt solution in water as a function of concentration.

Appendix A

Flowchart of Program (PGRMAC)



Appendix B

Listing of Computer Program (PGRMAC)

```
C     THIS PROGRAM PRINTS A SPECTRUM FILE FROM THE EMULATOR
C
      INTEGER*2 TYPE,MCA,SEG,STRTCH,LNGTDT,SPCOUI(64)
      INTEGER*2 SPCINI(64),BEGREC,ENDREC
      INTEGER*4 SPCIN(32),LVETME,RLTIME,AREA,DAREA,IDSMPL
      CHARACTER*1 SRTTME(4),SRTSEC(2),SRTDTE(8),OUTPUT(30)
      CHARACTER*1 CRCTRL,ANS,NRUN,NSMPL*3
      CHARACTER FUTP*8,SORC*10,LOCA*10,DLDT*10,AIRLN*8
      CHARACTER*30 OUT30,FILNM*15,FN1*15,FN2*15
      COMMON/PART1/ SRTTME,SRTSEC,SRTDTE,FN1,FN2,NRUN,NSMPL,MAXFLUID
      COMMON/PART2/ RLTIME,LVETME,MAXCHN,MAXSPN,LBEG,LEND,MAXAIR
      COMMON/PART3/ ATCFL,ATCFM,NCHN(700),NCNT(700),DIO,DIX,DML,DMM
      COMMON/PART4/ AREA,DNSTY,IO,IX,POWER,LUNINN,LUNOUT,IREC,TMP
      COMMON/PART5/ FUTP,SORC,LOCA,DLDT
      EQUIVALENCE(SPCOUT,SPCOUI),(SPCIN,SPCINI)
      EQUIVALENCE(OUT30,OUTPUT)
      REAL MUAIR,MUGLS,MUAL,MUFUEL,MUMAX,MUMIN,MAXCHN,MAXAIR,MAXFLUID
      DATA LUNCON/0/,OUTPUT/30*' '/
      DATA CRCTRL/'1'/,IER/0/
C
C     START
C
      LUNINN=1
      LUNOUT=3
      OPEN(17,FILE='PRN',STATUS='NEW')
      WRITE(LUNCON,90)
   90 FORMAT(/,' **************************************************',
     *        '****************')
      WRITE(LUNCON,100)
  100 FORMAT(/20X,'SPECTRUM PRINT ROUTINE',//1X,
     *        'ENTER THE DESIRED FILE NAME FROM MCA: '\)
      READ(LUNCON,5,ERR=8010) FILNM
    5 FORMAT(A15)
C     --------------------------------
      NSMPL=FILNM(5:7)
      NRUN=FILNM(8:8)
      FN1(1:4)=FILNM(1:4)
      FN1(5:15)='AIR1.CHN'
      FN2(1:8)=FN1(1:8)
      FN2(9:15)='.DAT'
C     ------------------------
      CALL CONVERT(NSMPL,IREC)
      OPEN(19,FILE='FUELDATA.DAT',STATUS='OLD',ACCESS='DIRECT',
     *     FORM='FORMATTED',RECL=70)
      READ(19,25,REC=IREC) IDSMPL,DNSTY,TMP,FUTP,SORC,LOCA,DLDT,
     *                    AIRLN,ADTV
   25 FORMAT(I3,1X,F6.4,1X,F4.1,1X,A5,1X,A10,1X,A10,1X,A8,1X,A8,
     *       1X,F5.2)
```

```
C     ----------------------------------------------------------
      OPEN(LUNINN,FILE=FN1,STATUS='OLD',ACCESS='DIRECT',
     #     RECL=32)
      OPEN(LUNOUT,FILE=FN2,STATUS='NEW')
      READ(LUNINN,REC=1) TYPE,MCA,SEG,SRTSEC,RLTIME,LVETME,
     #     SRTDTE,SRTTME,STRTCH,LNGTDT
      IF(TYPE .NE. -1) GO TO 8010
C     ----------------------------------------
      CALL CALCNTS(LUNINN,LUNOUT)
C     ----------------------------------------
      CALL CALAREA(LUNOUT)
      MAXAIR=MAXCHN
C     ------------------------
      IAIR=AREA
      MUAIR=0.0002132
      MUGLS=0.46654
      MUAL=0.6639
      XAIR1=5.08
      XAIR2=10.062+XAIR1
      XGLS=0.68
      XAL=0.079
      POWER=(MUAIR*XAIR2)+(MUGLS*XGLS)+(MUAL*XAL)
      I0=IAIR*EXP(POWER)
      DI0=SQRT(REAL(I0))
C     ------------------------------------------
C     CHANGE FN1,FN2 FOR EACH SAMPLE
C     ------------------------------------------
      FN1(1:8)=FILNM(1:8)
      FN1(9:15)='.CHN'
      FN2(1:8)=FILNM(1:8)
      FN2(9:15)='.DAT'
      LUNINN=11
      LUNOUT=13
      OPEN(LUNINN,FILE=FN1,STATUS='OLD',ACCESS='DIRECT',RECL=32)
      OPEN(LUNOUT,FILE=FN2,STATUS='NEW')
      READ(LUNINN,REC=1) TYPE,MCA,SEG,SRTSEC,RLTIME,LVETME,SRTDTE,
     #                  SRTTME,STRTCH,LNGTDT
      IF(TYPE .NE. -1) GO TO 8010
C     ------------------------------------------
      CALL CALCNTS(LUNINN,LUNOUT)
C
      CALL CALAREA(LUNOUT)
      MAXFLUID=MAXCHN
C     ------------------------------------------
      IX=AREA
      DIX=SQRT(REAL(IX))
      RAMAX=REAL(I0+DI0)/REAL(IX-DIX)
      RAMIN=REAL(I0-DI0)/REAL(IX+DIX)
      POWER1=MUAIR*(XAIR1)+MUGLS*XGLS+MUAL*XAL
      XFUEL=10.062
      MUMAX=(1.0/XFUEL)*(LOG(RAMAX)-POWER)
      MUMIN=(1.0/XFUEL)*(LOG(RAMIN)-POWER)
```

```
      MUFUEL=(MUMAX+MUMIN)/2.0
      DM1=MUFUEL-MUMAX
      DM2=MUFUEL-MUMIN
      DML=SQRT(DM1**2.0+DM2**2.0)
      DMM=DML/DNSTY
      ATCFL=MUFUEL
      ATCFM=ATCFL/DNSTY
C
      CALL PRNT1
C
      WRITE(LUNCON,50)
   50 FORMAT(//,' DO YOU WANT TO PRINT OUT CURRENT DATA (Y/N)? '\)
      READ(LUNCON,55,ERR=8010) ANS
   55 FORMAT(A1)
      IF (ANS .EQ. 'Y') THEN
         CALL PRNOUT
      ELSE
         GO TO 999
      ENDIF
  999 CLOSE(LUNINN)
 1000 STOP
 8000 IER=IER+1
 8010 IER=IER+1
      WRITE(LUNCON,8110) IER
 8110 FORMAT(' PRINT ERROR= ',I4)
      GO TO 1000
      END
```

Subroutine PRNOUT

```
      SUBROUTINE PRNOUT
      INTEGER*4 LVETME,RLTIME,AREA,DAREA
      CHARACTER*1 SRTTME(4),SRTSEC(2),SRTDTE(8)
      CHARACTER*1 NRUN,NSMPL*3,FN1*15,FN2*15
      CHARACTER FUTP*8,SORC*10,LOCA*10,DLDT*10,AIRLN*8
      COMMON/PART1/ SRTTME,SRTSEC,SRTDTE,FN1,FN2,NRUN,NSMPL,MAXFLUID
      COMMON/PART2/ RLTIME,LVETME,MAXCHN,MAXSPN,LBEG,LEND,MAXAIR
      COMMON/PART3/ ATCFL,ATCFM,NCHN(700),NCNT(700),DIO,DIX,DML,DMM
      COMMON/PART4/ AREA,DNSTY,IO,IX,POWER,LUNINN,LUNOUT,IREC,TMP
      COMMON/PART5/ FUTP,SORC,LOCA,DLDT
      REAL MAXCHN,MAXAIR,MAXFLUID
C
      WRITE(17,*) CHAR(14),'          AVIATION FUEL STUDIES'
      WRITE(17,10) FN1
   10 FORMAT(///5X,'**********************************************',
     # '*********************',//5X,'FILE NAME      : ',A15)
      WRITE(17,20) NSMPL,NRUN,SRTTME,SRTSEC,SRTDTE
   20 FORMAT(/5X,'SAMPLE I.D.    :',A4,//5X,'RUN NUMBER     :',A2,//,
     #        5X,'DATA COLLECTED AT :   ',2A1,':',2A1,':',2A1,2X,
     #        ' ON  ',2A1,'-',3A1,'-',3A1)
      WRITE(17,25) FUTP,SORC,LOCA,DLDT
   25 FORMAT(/5X,'FUEL TYPE      : ',A8,//5X,'SOURCE         : ',A10,
     # //5X,'LOCATION       : ',A10,//5X,'DELIVERY DATE : ',
     # A10)
      WRITE(17,30) MAXAIR,MAXFLUID,LBEG,LEND,MAXSPN
   30 FORMAT(/5X,'PEAK CHANNEL(AIR)   :',F7.2,//5X,
     #  'PEAK CHANNEL(FUEL) :',F7.2,//5X,'R. O. I.                :',I5,
     #  '  ...',I5,//5X,'PEAK COUNTS(FUEL)  :',I5)
      WRITE(17,35) RLTIME,LVETME,IO,DIO,IX,DIX
   35 FORMAT(/5X,'REAL TIME     :',I5,' seconds',//5X,
     # 'LIVE TIME     :',I5,' seconds',
     # //5X,'IO : ',I8,' +/-',F5.0,//5X,'IX : ',I8,' +/- ,
     # F5.0)
      WRITE(17,45) TMP
   45 FORMAT(/5X,'FUEL TEMPERATURE      : ',F7.1,'   C')
      WRITE(17,40) DNSTY,ATCFL,DML,ATCFM,DMM
   40 FORMAT(/5X,'FUEL DENSITY          :',F9.5,' (g/cm3)',//5X,
     #        'LINEAR ATTENU. COEFF. :',F9.5,'  +/-',F8.5,' (1/cm)',
     # //5X,'MASS ATTENU. COEFF.   :',F9.5,'  +/-',F8.5,' (cm2/g)')
      RETURN
      END
```

Subroutine PRNT1

```
      SUBROUTINE PRNT1
      INTEGER*4 LVETME,RLTIME,AREA,DAREA
      CHARACTER*1 SRTTME(4),SRTSEC(2),SRTDTE(8)
      CHARACTER*1 NRUN,NSMPL*3,FN1*15,FN2*15
      CHARACTER FUTP*8,SORC*10,LOCA*10,DLDT*10,AIRLN*8
      COMMON/PART1/ SRTTME,SRTSEC,SRTDTE,FN1,FN2,NRUN,NSMPL,MAXFLUID
      COMMON/PART2/ RLTIME,LVETME,MAXCHN,MAXSPN,LBEG,LEND,MAXAIR
      COMMON/PART3/ ATCFL,ATCFM,NCHN(700),NCNT(700),DIO,DIX,DML,DMM
      COMMON/PART4/ AREA,DNSTY,IO,IX,POWER,LUNINN,LUNOUT,IREC,TMP
      COMMON/PART5/ FUTP,SORC,LOCA,DLDT
      REAL MAXCHN,MAXAIR,MAXFLUID
C
      WRITE(0,5)
    5 FORMAT(30X,'AVIATION FUEL STUDIES',/5X,'****************** ,
     $      '**************************************************')
      WRITE(0,10) FN1
   10 FORMAT(5X,'FILE NAME      : ',A15)
      WRITE(0,20)  NSMPL,NRUN,SRTTME,SRTSEC,SRTDTE
   20 FORMAT(5X,'SAMPLE I.D.    :',A4,/5X,'RUN NUMBER     :',A2,/,
     $       5X,'DATA COLLECTED AT :  ',2A1,':',2A1,':',2A1,2X,
     $       ' ON  ',2A1,'-',3A1,'-',3A1)
      WRITE(0,25) FUTP,SORC,LOCA,DLDT
   25 FORMAT(5X,'FUEL TYPE      : ',A8,/5X,'SOURCE         : ',A10,
     $ /5X,'LOCATION       : ',A10,/5X,'DELIVERY DATE : ',A10)
      WRITE(0,30) MAXAIR,MAXFLUID,LBEG,LEND,MAXSPN
   30 FORMAT(5X,'PEAK CHANNEL(AIR)  :',F7.2,/5X,
     $  'PEAK CHANNEL(FUEL) :',F7.2,/5X,'R. O. I.             :',I5,
     $  '  ...',I5,/5X,'PEAK COUNTS(FUEL)  :',I5)
      RLTIME=RLTIME/50
      LVETME=LVETME/50
      WRITE(0,35)  RLTIME,LVETME,IO,DIO,IX,DIX
   35 FORMAT(5X,'REAL TIME    :',I5,/,5X,'LIVE TIME    :',I5,/5X,
     $        'IO : ',I8,' +/-',
     $        F5.0,/5X,'IX : ',I8,' +/-',F5.0)
      WRITE(0,45) TMP
   45 FORMAT(5X, FUEL TEMPERATURE      :  ,F7.1)
      WRITE(0,40) DNSTY,ATCFL,DML,ATCFM,DMM
   40 FORMAT(5X,'FUEL DENSITY           :',F9.5,/5X,
     $        'LINEAR ATTENU. COEFF. :',F9.5,' +/-',F8.5,/5X,
     $        'MASS ATTENU. COEFF.   :',F9.5,' +/-',F8.5)
      RETURN
      END
```

Subroutine CALCNTS (LIN,LOUT)

```
      SUBROUTINE CALCNTS(LIN,LOUT)
      INTEGER*2 BEGREC,ENDREC
      INTEGER*4 LVETME,RLTIME,AREA,DAREA,SPCIN(32)
      CHARACTER*1 SRTTME(4),SRTSEC(2),SRTDTE(8)
      CHARACTER*1 NRUN,NSMPL*3,FN1*15,FN2*15
      CHARACTER FUTP*8,SORC*10,LOCA*10,DLDT*10,AIRLN*8
      COMMON/PART1/ SRTTME,SRTSEC,SRTDTE,FN1,FN2,NRUN,NSMPL,MAXFLUID
      COMMON/PART2/ RLTIME,LVETME,MAXCHN,MAXSPN,LBEG,LEND,MAXAIR
      COMMON/PART3/ ATCFL,ATCFM,NCHN(700),NCNT(700),DIO,DIX,DML,DMM
      COMMON/PART4/ AREA,DNSTY,IO,IX,POWER,LUNINN,LUNOUT,IREC,TMP
      COMMON/PART5/ FUTP,SORC,LOCA,DLDT
      REAL MUAIR,MUGLS,MUAL,MUFUEL,MAXCHN
C
      ICHNNL=0
      CHANLI=ICHNNL-1
      LCHNNL=510
      CHANLL=LCHNNL-1
      BEGREC=CHANLI/8.
      ENDREC=CHANLL/8.
      DO 450 I=BEGREC+2,ENDREC+2
      READ(LIN,REC=I,ERR=8000)(SPCIN(K),K=1,8)
      KCHNL=8*(I-2)
      DO 400 J=1,8
      IF(KCHNL .GT. 1000) GO TO 8000
  420 WRITE(LOUT,410) KCHNL,SPCIN(J)
  410 FORMAT(1X,I5,I9)
  500 KCHNL=KCHNL+1
  400 CONTINUE
  450 CONTINUE
 8000 RETURN
      END
```

Subroutine CALAREA (LOUT)

```
      SUBROUTINE CALAREA(LOUT)
      INTEGER*2 BEGREC,ENDREC
      INTEGER*4 LVETME,RLTIME,AREA,DAREA,SPCIN(32)
      CHARACTER*1 SRTTME(4),SRTSEC(2),SRTDTE(8)
      CHARACTER*1 NRUN,NSMPL*3,FN1*15,FN2*15
      CHARACTER FUTP*8,SORC*10,LOCA*10,DLDT*10,AIRLN*8
      COMMON/PART1/ SRTTME,SRTSEC,SRTDTE,FN1,FN2,NRUN,NSMPL,MAXFLUID
      COMMON/PART2/ RLTIME,LVETME,MAXCHN,MAXSPN,LBEG,LEND,MAXAIR
      COMMON/PART3/ ATCFL,ATCFM,NCHN(700),NCNT(700),DIO,DIX,DML,DMM
      COMMON/PART4/ AREA,DNSTY,IO,IX,POWER,LUNINN,LUNOUT,IREC,TMP
      COMMON/PART5/ FUTP,SORC,LOCA,DLDT
      REAL MUAIR,MUGLS,MUAL,MUFUEL,MAXCHN,MY
C
      REWIND LOUT
      DO 300 I=1,500
         READ(LOUT,310,END=300) NCHN(I),NCNT(I)
 310     FORMAT(1X,I5,I9)
 300  CONTINUE
      LBEG=241
      LEND=421
      AREA=0
      MY=0.
      BEG1=REAL(NCNT(LBEG+1))
      BEG2=REAL(NCNT(LBEG+2))
      BEG3=REAL(NCNT(LBEG+3))
      HBEG=(BEG1+BEG2+BEG3)/3.0
      END1=REAL(NCNT(LEND+1))
      END2=REAL(NCNT(LEND))
      END3=REAL(NCNT(LEND-1))
      HEND=(END1+END2+END3)/3.0
      HAVG=0.5*(HBEG+HEND)
      DCHN=REAL(LEND-LBEG)
      SLOPE=(HEND-HBEG)/DCHN
      DO 320 L=LBEG+1,LEND+1
         DAREA=NCNT(L)
         AREA=AREA+DAREA
         H=SLOPE*(REAL(NCHN(L)-LBEG-1))+HBEG
         MY=MY+(REAL(NCNT(L))-H)*REAL(NCHN(L))
 320  CONTINUE
      EXCESS=0.5*(HBEG+HEND)*DCHN
      MAXCHN=MY/(REAL(AREA)-EXCESS)
      DO 350 I=LBEG+1,LEND+1
         ERR=REAL(NCHN(I))-MAXCHN
         IF(ABS(ERR) .LT. 0.5) THEN
            MAXSPN=NCNT(I)
            GO TO 400
         ELSE
            GO TO 350
         ENDIF
 350  CONTINUE
 400  RETURN
      END
```

Subroutine CONVERT (NSPL,IRC)

```
      SUBROUTINE CONVERT(NSPL,IRC)
      INTEGER*4 LVETME,RLTIME,AREA,DAREA
      CHARACTER*1 SRTTME(4),SRTSEC(2),SRTDTE(8)
      CHARACTER*1 NRUN,NSMPL*3,FN1*15,FN2*15
      CHARACTER FUTP*8,SORC*10,LOCA*10,DLDT*10,AIRLN*8
      CHARACTER*1 CR1,CR2,CR3,NSPL*3
      COMMON/PART1/ SRTTME,SRTSEC,SRTDTE,FN1,FN2,NRUN,NSMPL,MAXFLUID
      COMMON/PART2/ RLTIME,LVETME,MAXCHN,MAXSPN,LBEG,LEND,MAXAIR
      COMMON/PART3/ ATCFL,ATCFM,NCHN(700),NCNT(700),DIO,DIX,DML,DMM
      COMMON/PART4/ AREA,DNSTY,IO,IX,POWER,LUNINN,LUNOUT,IREC,TMP
      COMMON/PART5/ FUTP,SORC,LOCA,DLDT
C
      CR1=NSPL(1:1)
      CR2=NSPL(2:2)
      CR3=NSPL(3:3)
      N1=ICHAR(CR1)
      N2=ICHAR(CR2)
      N3=ICHAR(CR3)
      ID=(N1-48)*100+(N2-48)*10+(N3-48)
      IRC=ID
      RETURN
      END
```

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16. Abstract
A technique for monitoring variability in the nuclear absorption characteristics of aviation fuels has been developed. It is based on a highly collimated low energy gamma radiation source and a sodium iodide counter. The source and the counter assembly are separated by a geometrically well-defined test fuel cell. A computer program for determining the mass attenuation coefficient of the test fuel sample, based on the data acquired for a preset counting period, has been developed and tested on several types of aviation fuel.

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