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(54) **Determining fissile content of nuclear fuel elements**

(57) Determination of fissile fuel eg. U235 content of fuel elements containing burnable poisons eg. gadolinium (a strong neutron absorber) entails selection of sequential zones of the element whereat gamma ray emission is detected with scintillator/photomultipliers 42(1–n) and attributed to the fissile fuel and according other materials by peak height analysers 44, 44' respectively operating in two energy ranges. The counts are corrected at each zone, according to the cladding thickness measured by ultrasonic sensor 22, density of the fuel material measured by absorption of γ-rays from an auxilliary source at 24 and the weight of the burnable poison measured by magnetic sensor 26 to determine the weight of fissile fuel.

Infra-red sensors P_1-P_n monitor movement of elements to control stepping motor 14 via controller 18 and circuit 16. Controller 18 also synchronises the peak height analysers by means of clock outputs C_1-C_n to enable spatial separation of element gamma activity measurements from other measurements. Abnormal enrichment of individual fuel pellets within the elements is also detected.
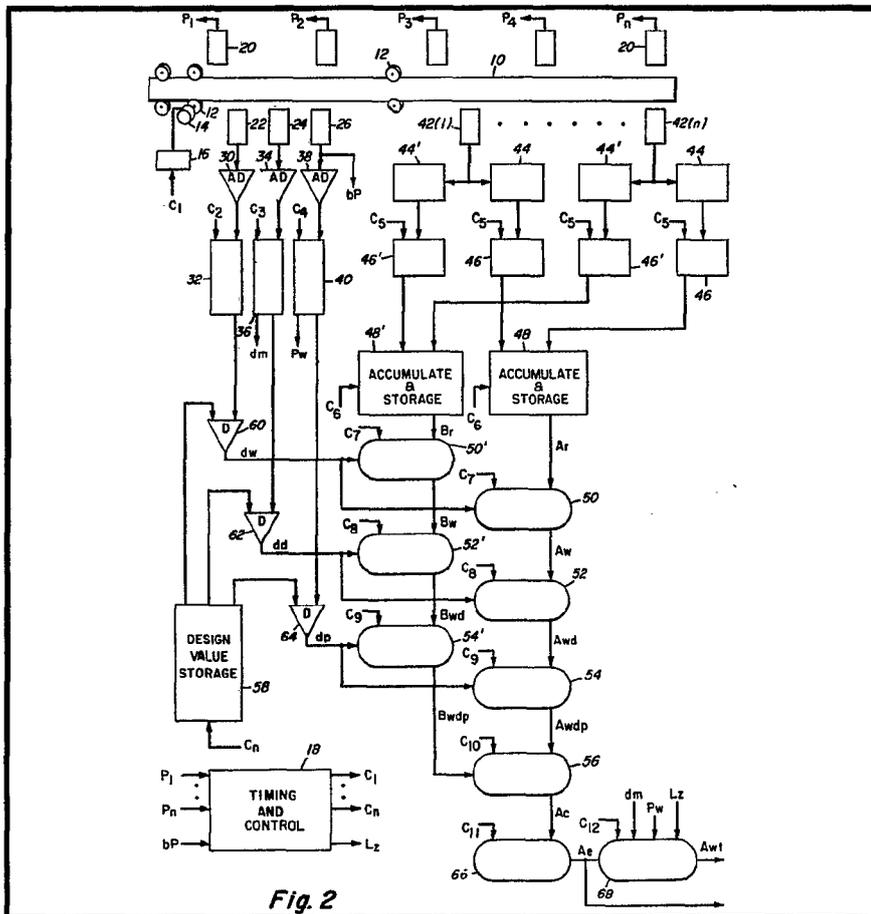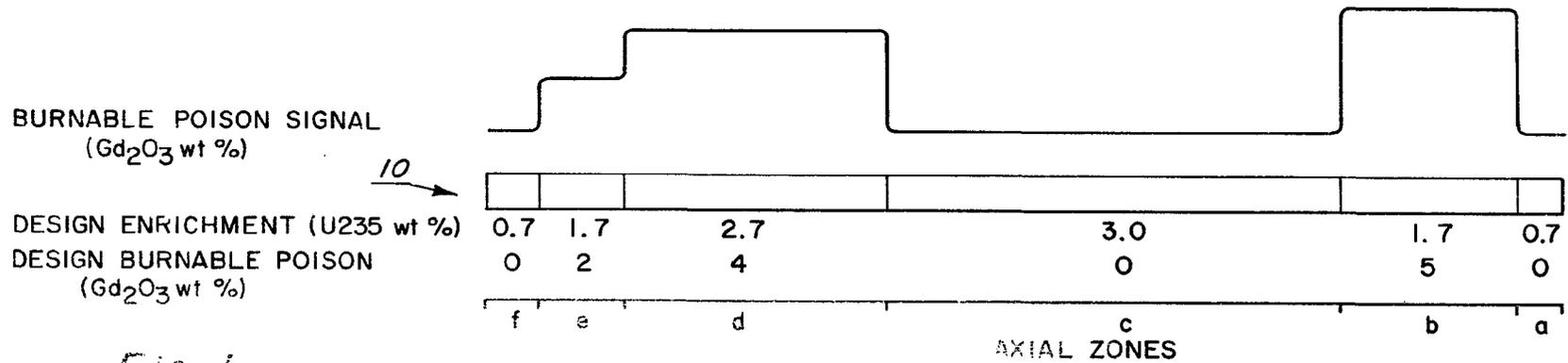
Fig. 2

BURNABLE POISON SIGNAL
(Gd$_2$O$_3$ wt %)

10 →

| DESIGN ENRICHMENT (U235 wt %) | 0.7 | 1.7 | 2.7 | 3.0 | 1.7 | 0.7 |
| DESIGN BURNABLE POISON (Gd$_2$O$_3$ wt %) | 0 | 2 | 4 | 0 | 5 | 0 |

f　e　d　c　b　a
AXIAL ZONES

Fig. 1

Zone	Length of Zone (inches)	Measured Density (% Theoretical)	Measured Wall Thickness (inches X 10^{-3})	Measured Gadolinium (wt %)	Enrichment (wt %)	Measured U-235 (Grams)
1	6.12	95.426	32.19	0.000	0.713	0.83
2	6.12	95.676	32.19	0.016	2.209	2.65
3	12.15	95.609	32.19	4.063	1.707	3.80
4	35.93	95.410	32.19	0.215	2.219	15.86
5	72.06	95.913	32.19	3.760	1.705	23.22
6	12.46	95.361	32.19	0.004	2.246	5.51
7	4.98	95.601	32.19	0.011	0.758	0.80

Fig. 3
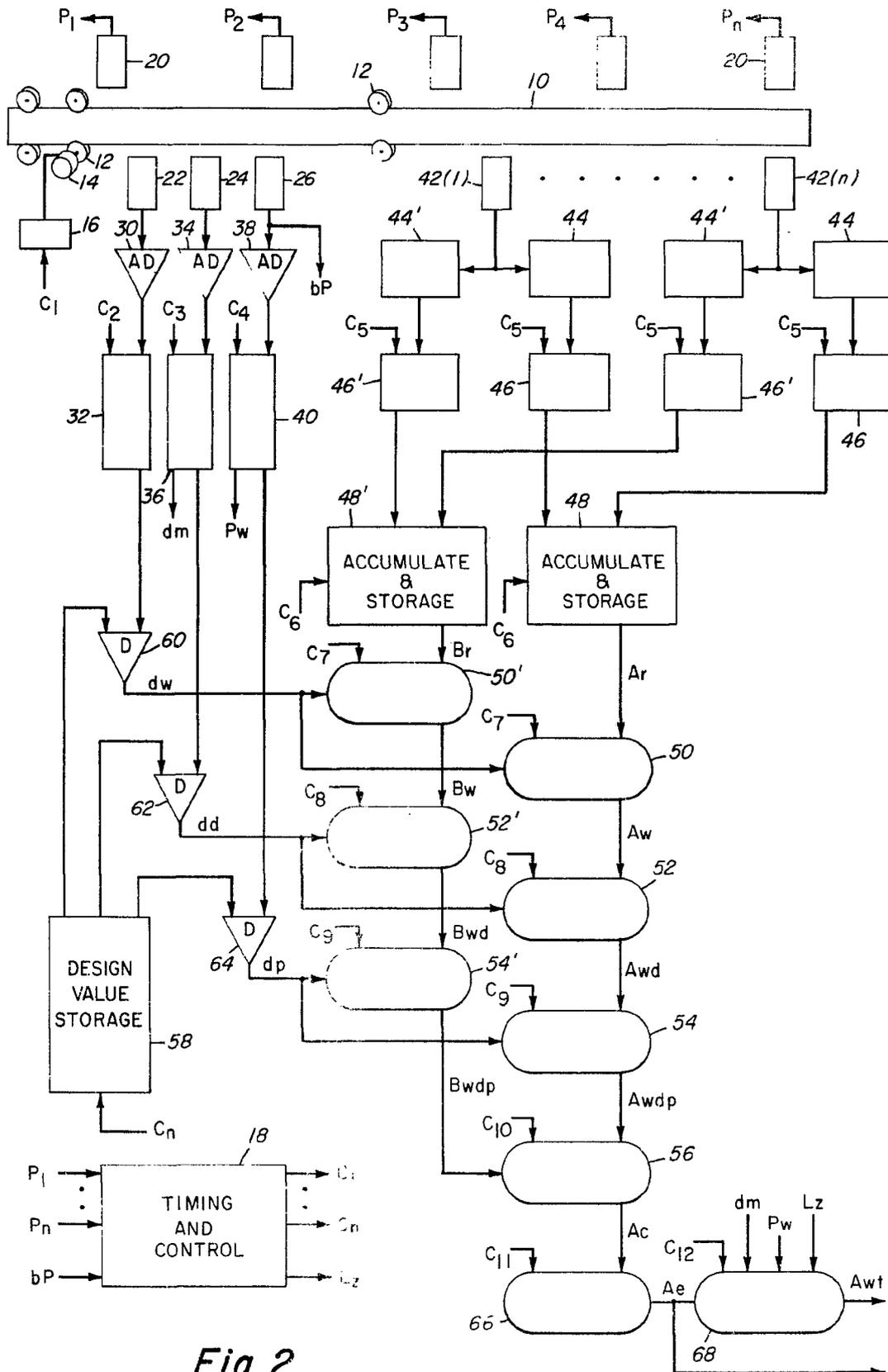
Fig. 2

SPECIFICATION

Determining fissile content of nuclear fuel elements

This invention relates to the determination of the fissile fuel content of fuel for nuclear reactors. Such nuclear reactors are discussed for example in "Nuclear Power Engineering", M. M. El-Wakil, McGraw-Hill Book Company, Inc., 1962.

Nuclear reactors are typically refueled periodically with an excess of fuel sufficient to maintain operation throughout an operating cycle.

This excess of fuel results in an excess of reactivity which requires a control system of sufficient strength to maintain the effective multiplication factor at unity during reactor operation. The control system customarily comprises neutron absorbing or poison materials that serve to control the neutron population by nonfission absorption or capture of neutrons. Typically, the control system includes mechanical control in the form of a plurality of selectively actuatable poison containing control rods or the like which can be inserted into and withdrawn from the core as required.

Nuclear fuels include uranium and/or plutonium in suitable form. For example, in commonly used fuel for water cooled and moderated nuclear power reactors the fuel comprises uranium dioxide (UO_2) in which from about 0.7 to 5.0 percent is fissile U-235 mixed with fertile U-238. Such nuclear fuel typically is in the form of sintered pellets contained in an elongated cladding tube to form a fuel element or rod as shown, for example, in U. S. Patent No. 3,378,458. Such fuel elements are arranged in groups and supported in separately replaceable fuel assemblies in the core of the reactor. A typical fuel assembly is shown for example in U. S. Patent No. 3,689,358.

To decrease local power peaking and to achieve desired power distribution, it is known to vary the fuel enrichment radially from element-to-element within the fuel assembly and axially along the lengths of the elements. That is, the fissile fuel content of a fuel element may be varied from zone-to-zone along its length.

It is also known to include in the fuel core a burnable poison such as gadolinium which is a strong neutron absorber but is converted by neutron absorption to an isotope of low control worth (neutron absorbing capacity). Such use of burnable poisons decreases the amount of mechnical control required and, by appropriate arrangement of the burnable poison, improvements in power distribution can be achieved.

Such burnable poisons frequently are incorporated in the fuel elements in a mixture with selected portions of the nuclear fuel. As in the case of fissile fuel content, the burnable poison content of a fuel element may be varied from zone-to-zone along its length. A zoned arrangement of burnable poison is shown, for example, in U. S. Patent No. 3,799,839.

It is desirable for quality control and identification purposes during nuclear fuel handling and fuel element and fuel assembly manufacturing processes to provide rapid nondestructive methods for determining accurately the amount, enrichment and location of the fissile fuel along the length of a fuel element.

An early method for the nondestructive determination of the relative fissile concentration or enrichment of fuel material can be called "passive scanning". Such a method is based upon the quantitative detection of gamma rays of characteristic energy emitted during the natural radioactive decay of a fissile material such as U-235. Such a method is discussed by G. H. Morrison et al in an article entitled "Determination of Uranium-235 by Gamma Scintillation Spectrometry", in Analytical Chemistry, Vol. 29, No. 12, December 1957, pages 1770 and 1771.

Further development of this passive scanning method for enrichment measurement involved a correction of the U-235 indication based upon the detection of gamma rays emitted by daughter products of U-238. The method and systems employing such correction are discussed, for example, by C. N. Jackson, Jr., in an article entitled "Enrichment Tester for 0.15 to 3.0 Weight Per Cent U-235 Uranium Fuel" in Materials Evaluation, August 1966, pages 431–435, and by J. T. Russell in U. S. Patent No. 3,389,254.

Since U-235 has a relatively long half-life its spontaneous disintegration rate and consequent gamma ray emission is low. Because of this and because of the statistical nature of the gamma ray emission, the scanning times required for accurate U-235 determination by the passive scanning method are undesirably long for production fuel use, particularly for low enrichment fuel material. For example, it was found that fuel elements in the order of 4.5 meters long containing fuel of 2 to 3 percent enrichment required a scanning time in the order of forty minutes where a single gamma ray detector was used to obtain suitable accuracy in enrichment measurement.

The throughput can be increased (that is, the scanning time for fuel elements can be reduced) by the use of a plurality of gamma ray detectors serially arranged adjacent to the fuel element being scanned. The gamma ray counts from the detectors attributable to each local segment of the fuel element are accumulated and summed, thus decreasing the scanning time required for a given accuracy in proportion to the square root of the number of detectors employed. An arrangement of a plu-

rality of radiation detectors for sorting radiation emissive material is shown by F. T. Holmes in U. S. Patent No. 2,717,693.

A method for the simultaneous nondestruc-
5 tive determination of the enrichment and fissile content of fuel material can be called "active scanning". In this method the fuel element is moved past a narrow beam of neutrons of selected energy and the gamma
10 radiation from successive local portions of the element resulting from the neutron-induced fission of the fissile material, such as U-235, is detected. The radiation count from each local portion is a function of the intensity of
15 the neutron activation beam and the concentration of U-235 in the local portion. Active fissile content analyzer systems have been described, for example, in German patent publication 1,923,983 (published 20 Novem-
20 ber 1969) and by R. A. Pritchett in U. S. Patent No. 3,018,374.

Active scanning systems have been placed in use in commercial nuclear fuel manufacturing facilities because of the accuracy of fissile
25 content and enrichment determinations and the favorable scanning speed afforded thereby. However, in the case of fuel elements containing a burnable poison mixed with the fuel material, the neutron activation or active
30 scanning method is not found effective. Such fuel elements may contain burnable poison, such as gadolinium, in amounts in the order of 1–10 weight percent. Such amounts of gadolinium render the fuel pellet or body
35 substantially black to neutrons. That is, the activation neutrons are absorbed by the burnable poison at the surface of the body and do not penetrate sufficiently to provide adequate activation of the fissile material. Furthermore,
40 the variability of the burnable poison concentration along the length of the fuel rod tends to mask the measurement of the fissile fuel content.

Present quality control techniques for the
45 determination of enrichment and fissile content of gadolinium bearing fuel involve destructive measurement of presumably representative samples and are undesirable because they are not a direct measurement and they
50 are expensive and labor intensive.

Thus there remains a need for nondestructive methods and means for determining rapidly, accurately and simultaneously the fissile content, enrichment and location of fuel
55 material which may also contain amounts of burnable poison.

In accordance with the method and apparatus of the invention, a fuel element is scanned by moving it past one or more detec-
60 tors responsive to the gamma rays emitted from the fuel material due to natural radioactive decay. Pulses from the detectors, which have magnitudes proportional to the energy of the gamma rays, are applied to pulse height
65 analyzers and separated into two channels

according to predetermined energy ranges. The pulses in each channel are counted and the counts stored in correspondence with sequential zones along the length of the fuel
70 element. One channel contains the count of gamma ray primarily attributable to the fissile material (e.g., U-235) while the other channel contains the count of the gamma rays (of different energy) primarily attributable to the
75 daughter products of U-238.

Means are provided for determining the burnable poison (e.g., gadolinium) content, the fuel material density and the cladding thickness at each zone and the fissile material
80 and daughter product counts are corrected accordingly.

The fissile material (U-235) counts are then further corrected to remove the influence of the corrected U-238 daughter product count
85 and from the thus corrected U-235 count the weight percent of U-235 in each zone is determined.

From the weight percent of U-235, the weight percent of gadolinium and the density
90 of the fuel material in the zones and from the volumes of the zones, the weight of U-235 in each of the zones can be determined.

The present invention will be further described, by way of example only, with refer-
95 ence to the accompanying drawings, in which:

Figure 1 illustrates an example fuel element having zone-to-zone variations in burnable poison content and fuel enrichment axially
100 along its length;

Figure 2 illustrates in functional diagram form an arrangement for performing the method of the invention; and

Figure 3 is a chart of data obtained in
105 testing an example fuel element in accordance with the invention.

For the purpose of illustrating the problem solved by the present invention there is illustrated in Fig. 1 an example fuel element 10
110 wherein the fuel enrichment and the amount of burnable poison varies from zone-to-zone along the length of the fuel element. In the illustrated example the changes in enrichment and burnable poison content are coincident,
115 that is, both enrichment and burnable poison content are constant in any given zone. This is a typical arrangement but not a requirement of the invention, that is, the enrichment could be varied within a burnable poison zone or
120 vice versa.

An example arrangement of apparatus for carrying out the method of the invention is illustrated in functional diagrammatic form in Fig. 2, it being understood that the timing,
125 control, storage and calculational functions illustrated therein normally will be carried out by a suitably programmed data processing device as is well-known in the art.

A fuel element 10 to be scanned typically
130 comprises a column of fuel pellets sealed in a

cladding tube formed of a zirconium alloy
with an outside diameter of about 12.7 mm
and a wall thickness in the order of 0.80 mm.
The length of the fuel column is typically in
5 the order of 3.5 m. The fuel element 10 is
driven and guided through the scanning sta-
tion by, for example, a plurality of suitably
positioned grooved wheels 12 one or more of
which is driven by a stepping motor 14 which
10 is controlled by a suitable driving circuit 16.
The driving circuit 16 receives actuation con-
trol signals C_1 from a master timing and
control system 18.
    Positioned along the path of the fuel ele-
15 ment 10 are a plurality of fuel element posi-
tion sensors 20 which may be of a known
pulsed infrared photoelectric type. (Such de-
vices are available for example from OPCON
Inc., Everett, Washington.) Signals P_1-P_n from
20 sensors 20 are fed to the timing and control
system 18 for control of the frequency of the
stepping motor actuation signal C_1 and hence
the speed of the fuel element through the
scanning station.
25   In one mode of operation a plurality of
sequential zones of predetermined length of
the fuel material in element 10 are deter-
mined and identified from the rod position
sensor signals and from the predetermined
30 fuel element speed and a zone identification
pattern of signals is established in the timing
and control system 18. The lengths of the
zones may be selected arbitrarily. For exam-
ple, each zone may encompass several fuel
35 pellets or may be the length of a fuel pellet
whereby the fissile fuel content of each pellet
is determined or each zone may be a fraction
of the length of a fuel pellet where a higher
degree of scrutiny of the fissile fuel content is
40 desired. (An alternate mode of zone determi-
nation based upon the distribution of burnable
poison in the fuel is described hereinafter.)
    Also positioned along the path of the fuel
element 10 are the following: a cladding wall
45 thickness sensor 22, a fuel material density
sensor 24, a burnable poison content sensor
26 and a plurality of gamma ray detectors
42(1)–24(n).
    The cladding wall thickness sensor 22 may
50 be of any suitable type, for example, an
ultrasonic wave system which determines the
wall thickness by detecting the time interval
between the wave reflections from the outer
and inner surfaces of the claddings. (Such
55 devices are available for example from Sonic
Instrument Inc,. Trenton, New Jersey.)
    Signals from the wall thickness sensor 22
are preferably digitized (if not already in digi-
tal form) by an analog-to-digital converter 30
60 and stored zone-by-zone for subsequent use in
a storage unit 32 the zone identification infor-
mation being provided from the control sys-
tem 18 over a connection C_2. (Although
shown as a single connection, it is to be
65 understood that the connections C_1-C_n be-

tween the control system 18 and the other
elements of the system provide the number of
timing, control and information signal paths
as required in each case.)
70   Preferably wall thickness readings are taken
from the sensor 22 under control of periodic
clock signals from control circuit 18 (for ex-
ample at distances of 5 mm along the fuel
element length) and the storage unit 32 in-
75 cludes means for processing these wall thick-
ness signals to determine the average wall
thickness along each zone whereby signals
representative of the average wall thickness at
each zone are stored for subsequent use.
80   The fuel material density sensor 24 may be
a known gamma ray densitometer arrange-
ment comprising a suitable gamma beam
source and a gamma ray detector positioned
on opposite sides of the fuel element. The
85 gamma beam is attenuated in its passage
through the fuel element in proportion to the
fuel material density and, hence, the output
signal from the gamma ray detector related
monotonically to the fuel material density.
90   Signals from the density sensor 24 prefera-
bly are digitized by an analog-to-digital con-
verter 34 and are stored zone-by-zone for
subsequent use in a storage unit 36 the zone
identification information being provided from
95 control system 18 over a connection C_3.
    Preferably the fuel material density readings
are taken from the sensor 24 under control of
periodic clock signals from control circuit 18
(for example at distances of 5 mm along the
100 fuel element) and the storage unit 36 includes
signal averaging means whereby signals rep-
resentative of the average density of the fuel
material in each zone are stored for subse-
quent use.
105   The burnable poison content sensor 26 may
be of the magnetic type wherein the amounts
and distribution of a paramagnetic burnable
poison, such as gadolinium, are determined
from the changes in paramagnetic susceptibil-
110 ity as the fuele element is passed through a
magnetic field.
    Signals from the burnable poison sensor 26
preferably are digitized by an analog-to-digital
converter 38 and the average burnable poison
115 content in each zone is determined and stored
for subsequent use by a suitable storage unit
40.
    Gamma ray detectors for detecting the
gamma rays emitted from the fuel material
120 due to natural radioactive decay are illustrated
in Fig. 2 as sensors 42(1)–42(n). Preferably
the gamma ray sensors 42(1)–42(n) are of the
scintillator type comprised, for example, of
slabs of scintillator material such as sodium
125 iodide in the order of 1.3 cm thick and 4 cm
outside diameter and formed with a central
hole for passage of the fuel element 10 there-
through. The scintillator slabs are coupled to
photomultiplier tubes for detection of the scin-
130 tillations and conversion thereof to electrical

pulses. The detectors may be of the solid state type such as lithium drifted germanium or intrinsic germanium. The detectors 42(1)–42(n) also include the required pream-
5 plifiers and pulse shapers. Such detectors and various other aspects of radiation detection and measurement are discussed, for example, by W. J. Price in "Nuclear Radiation Detec- tion", McGraw Hill Book Company, 1964.
10 The signals from each of the detectors 42(1)–42(n) are fed in parallel to a respective pair of single channel analysers 44 and 44' the purpose of which is to separate the pulses from the detectors into two groups, namely,
15 the pulses resulting from gamma rays of en- ergy corresponding to a characteristic energy peak of the fissile material and the pulses resulting from gamma rays of energy greater than such characteristic energy peak.
20 Thus the analysers 44 and 44' are in es- sence amplifer circuits having upper and lower input thresholds whereby response of the circuit is limited to the predetermined amplitude range or "window" determined by
25 the threshold settings. Such analysers are well known, are discussed, for example, in U. S. Patent No. 3,114,835 and are commercially available, for example, from Tennelec Instru- ment Company, Inc., Oak Ridge, Tennessee
30 as Analyzer Model TC 214.
In accordance with this invention, where the fissile material is U-235 the analysers 44 are adjusted to respond to detector pulses resulting from gamma rays having energy in
35 the range of about 155–220 Kev to thus include the 184 Kev peak characteristic of U- 235. The analysers 44' are adjusted to re- spond to detector pulses resulting from gamma rays having energy in the range of
40 about 245–1190 Kev due to the radioactive daughters of U-238 whereby a U-238 daugh- ter correction count can be developed.
Output pulse signals from analysers 44 and 44' are fed to respective pulse counters 46
45 and 46' wherein counts of the pulses are accumulated. Under control of clock pulses over connections C_5 from control circuit 18, the counts in counters 45 and 46' periodically (e.g., every 300 ms) are fed to respective
50 accumulate and storage units 48 and 48' and the counters 46 and 46' are reset.
The accumulate and storage units 48 and 48' receive zone identification information over connections C_6 from control circuit 18
55 whereby the U-235 counts from counter 46 are received and stored zone-by-zone in unit 48 and the U-238 daughter counts are re- ceived and stored zone-by-zone in unit 48'. As the serially arranged multiple detectors
60 42(1)–42(n) each scan each of the fuel material zones in succession, the U-235 and U-238 daughter counts from each of the detectors for each of the zones are accumu- lated in accumulate and storage units 48 and
65 48'. Thus at completion of the scanning of

the fuel element 10, the units 48 and 48' will have accumulated the U-235 and U-238 daughter counts for each of the zones from each of the detectors 42(1)–42(n).
70 As mentioned hereinbefore, the use of mul- tiple detectors and the accumulation of the counts therefrom to reduce scanning time is discussed in U. S. Patent No. 2,717,693.
After completion of the scanning of the fuel
75 element 10 by the detectors 42(1)–42(n) and accumulation and storage of the U-235 and U-238 daughter counts in units 48 and 48', a series of corrections, namely, correction of the U-235 and U-238 daughter counts for clad-
80 ding wall thickness, fuel material density and burnable poison content and further correction of the U-235 count by the corrected U-238 daughter count, are performed. These correc- tion functions may be performed by well-
85 known data processing means illustrated in Fig. 2 as function circuits 50, 50', 52, 52', 54, 54' and 56. Connections C_7–C_{10} from the timing and control circuit 18 provide suitable control signals to the function circuits.
90 In the corrections of the U-235 and U-238 daughter counts for wall thickness, density and burnable poison content it is preferred to use values proportional to the deviation of these quantities from their design values, illus-
95 trated in Fig. 2 as input signals dw, dd and dp to function circuits 50 and 50', 52 and 52' and 54 and 54', respectively. The devia- tion signals dw, dd and dp are provided as follows: Design values of the cladding wall
100 thickness, density of fuel material and burna- ble poison content of each zone are entered and stored in a storage unit 58. When the stored measured values of wall thickness, den- sity and burnable poison content are called
105 out of storage units 32, 36 and 40, they are fed, along with the corresponding design va- lues from storage unit 58, to respective com- parison circuits such as differential amplifiers 60, 62 and 64 whereby the deviation signals
110 dw, dd and dp are provided.
The process of correcting the U-235 and U- 238 daughter counts is as follows: the U-235 and U-238 daughter counts are called from the storage units zone-by-zone and in parallel,
115 the uncorrected U-235 count being desig- nated a count signal Ar and the uncorrected U-238 daughter count being designated a count signal Br.
The count Ar and the signal dw are applied
120 to the function circuit 50 which provides an output count signal Aw according to the fol- lowing relationship:

$$125 \quad (1) \qquad Aw = \frac{AR}{{_a}K_1 dw} \quad \text{where}$$

Aw is the U-235 count corrected for clad- ding wall thickness,
130 Ar is the uncorrected U-235 count,

e is the base of the natural system of logarithms,

dw is the deviation of the wall thickness from design value, and

5   K_1 is a wall thickness correction constant.

(It is noted that the constants K_1–K_{11} will be defined more specifically hereinafter.)

The count Br and signal dw are applied to the function circuit 50' which provides an

10 output count signal Bw according to the following relationship:

$$(2) \quad Bw = \frac{Br}{_eK_4dw} \quad where$$

15

Bw is the U-238 daughter count corrected for cladding wall thickness,

Br is the uncorrected U-238 daughter

20 count, and

K_4 is a wall thickness correction constant.

The count Aw and the signal dd are applied to function circuit 52 which provides an output count signal Awd according to the follow-

25 ing relationship:

$$(3) \quad Awd = \frac{Aw}{1 + K_2dd} \quad where$$

30

Awd is the U-235 count corrected for cladding wall thickness and fuel material density,

dd is the deviation of fuel material density

35 from design value, and

K_2 is a density correction constant.

The count Bw and the signal dd are applied to function circuit 52' which provides an output count signal Bwd according to the

40 following relationship:

$$(4) \quad Bwd = \frac{Bw}{1 + K_5dd} \quad where$$

45

Bwd is the U-238 daughter count corrected for cladding wall thickness and fuel material density, and

K_5 is a density correction constant.

50 The count Awd and the signal dp are applied to function circuit 54 which provides an output count signal Awdp according to the following relationship:

55

$$(5) \quad Awdp = \frac{Awd}{1 + K_3dp} \quad where$$

Awdp is the U-235 count corrected for

60 cladding wall thickness, fuel material density and burnable poison content,

dp is the deviation of burnable poison content from design value, and

K_3 is a burnable poison content correction

65 constant.

The count Bwd and the signal dp are applied to function circuit 54' which provides an output count signal Bwdp according to the following relationship:

70

$$(6) \quad Bwdp = \frac{Bwd}{1 + K_6dp} \quad where$$

75 Bwdp is the U-238 daughter count corrected for cladding wall thickness, fuel material density and burnable poison content, and

K_6 is a burnable poison content correction

80 constant.

The counts Awdp and Bwdp are applied to function circuit 56 which provides an output count signal Ac according to the following relationship:

85

$$(7) \quad Ac = Awdp - K_7Bwdp \quad where$$

Ac is the finally corrected U-235 gamma ray count, and

90 K_7 is a U-238 daughter count correction constant.

Two additional function circuits are provided. A function circuit 66 converts the finally corrected U-235 count Ac to a signal Ae

95 indicative of the U-235 enrichment (e.g., weight percent U-235) in each zone while a function circuit 68 determines the weight of U-235 zone-by-zone.

Thus the function circuit 66 receives the

100 corrected U-235 count signal Ac (and zone position and control signals on C_{11}) and provides an output signal Ae according to the following relationship:

105 $(8) \quad Ae = K_8Ac + Kg \quad where$

Ae is the average enrichment in the zone in weight percent, and

K_8 and K_9 are enrichment calibration con-

110 stants.

The enrichment signal Ae can be taken as a useful output from the system.

The weight of U-235 in each zone is determined from the weight percents of U-235 and

115 burnable poison in the zone and from the density and volume of each zone. In the usual production case the diameter of the fuel pellets is carefully controlled and, therefore, can be taken as constant.

120 Thus the function circuit 68 receives the U-235 enrichment signal Ae, and signs dm, pw and Lz from storage units 36 and 40 and control circuit 18, respectively, and provides the output signal Awt according to the follow-

125 ing relationship:

$(9) \qquad Awt = K_{10} \, Ae \, dm \, Lz \, (1 - .01 \, Pw)$
$(10.95 - .034 \, Pw) + K_{11}$

130 where:

Awt is the weight of U-235 in the zone,
dm is the measured density of the fuel
material in the zone in percent of theoretical
density.

5   Lz is the measured length of the zone,
Pw is the measured weight percent of bur-
nable poison in the zone,
K_{10} is a conversion constant,
K_{11} is a constant which accounts for bias in
10   measurements compared to certified stan-
dards,
the term .01 is a factor for conversion of
weight percent to weight fraction,
the term 10.95 represents the theoretical
15   density of UO_2 fuel pellets in gm/cc without
burnable poison, and
the term 0.34 represents the change in
pellet density due to the addition of one
percent burnable poison content.

20   Where the zone lengths are selected to be
uniform the zone length signal Lz is then a
constant. However, for some applications it is
desirable to employ variable zone lengths
such as, for example, in fuel element arrange-
25   ments such as shown in Fig. 1. In this exam-
ple the design values of fuel enrichment and
the burnable poison content are uniform
throughout each burnable poison zone but
both fuel enrichment and burnable poison
30   content change from zone-to-zone. In such a
case the variable zone lengths of the burnable
poison can be determined using the burnable
poison sensor 26 and the timing and control
circuit 18 and used as the zone lengths Lz in
35   the fissile content determining method of the
invention illustrated in Fig. 2. In this event
the zone lengths are determined from the
changes in the burnable poison signal at the
interfaces between zones. That is, the signal
40   bp from the burnable poison sensor 26 is fed
to the timing and control circuit 18 and the
changes in the level of the signal bp are
therein employed (together with the fuel ele-
ment position signals P_1-P_n) to develop the
45   zone identification and zone length signals Lz.
The constants K_1-K_{11} set forth in the fore-
going relationships (1)–(9) are defined more
specifically as follows:
K_1 represents the exponential dependence
50   coefficient of observed U-235 counts on
cladding thickness. K_1 may be determined by
obtaining long duration U-235 gamma ray
counts of aged fuel in two elements of differ-
ent known cladding thickness, substituting the
55   counts in relationship (1) and solving for K_1.
K_2 is a U-235 count density correction
constant and represents the fractional varia-
tion of corrected U-235 counts for a unit
percentile change in density. K_2 is determined
60   by obtaining the gamma ray count of aged
fuel of given burnable poison content but of
two different and known densities in elements
of given cladding thickness, substituting the
counts in relationship (3) and solving for K_2.
65   K_3 is a U-235 count burnable poison correc-

tion constant which represents the fractional
variation of the corrected U-235 counts for a
unit percentile change in burnable poison con-
tent. K_3 is determined by obtaining the
70   gamma ray count of two elements of given
cladding thickness containing aged fuel of
given density but of different known burnable
poison content, substituting the counts in rela-
tionship (5) and solving for K_3.
75   K_4 represents the exponential dependence
coefficient of observed U-238 counts on
cladding thickness. K_4 is determined by ob-
taining long duration U-238 gamma ray
counts of aged fuel in two elements of differ-
80   ent known cladding thickness, substituting the
counts in relationship (2) and solving for K_4.
K_5 is a U-238 count density correction
constant and represents the fractional varia-
tion of corrected U-238 counts for a unit
85   percentile change in density. K_5 is determined
by obtaining the gamma ray count of aged
fuel of given burnable poison content but of
two different and known densities in elements
of given cladding thickness, substituting the
90   counts in relationship (4) and solving for K_5.
K_6 is a U-238 count burnable poison correc-
tion constant which represents the fractional
variation of the corrected U-238 counts for a
unit percentile change in burnable poison con-
95   tent. K_6 is determined by obtaining the
gamma ray count of two elements of given
cladding thickness containing aged fuel of
given density but of different known burnable
poison content, substituting the counts in rela-
100   tionship (6) and solving for K_6.
K_7 is the U238 daughter count correction
constant. It represents the fraction of the
corrected U-238 counts that must be sub-
tracted from the corrected U-235 counts to
105   obtain the net counts Ac due only to U-235
decay. K_7 may be determined by measuring
the U-235 and U-238 corrected counts Awdp
and Bwdp (from relationships (5) and (6)) for
fuel zones of known and same enrichment but
110   of two different ages. (Age refers to the
elapsed time since the last chemical process-
ing of the uranium in which the Th and Pu
daughter products of U-238 are separated
from the material.)
115   Then:

$$K_7 = \frac{Awdp(2) - Awdp(1)}{Bwdp(2) - Bwdp(1)}$$

120
K_8 and K_9 are enrichment calibration con-
stants which are determined by obtaining the
gamma ray count of fuel element zones of
given same fuel material density, cladding
125   wall thickness and burnable poison content
but of different known enrichments. The re-
sulting counts are substituted into relationship
(8) with iteratively selected values of K_8 and
K_9 until the difference between the measured
130   average enrichment Ae and the known aver-

age enrichment is minimized.

K_{10} is a conversion constant which converts the units of measurement into grams. It is determined by measuring calibration standard
5 elements of known U-235 weight, density, burnable poison content, enrichment and length.

K_{11} is a nuclear materials management constant. It is determined by comparing the mea-
10 sured values of weight of U-235 of standard elements of known values. This comparison is performed over a relatively long time period (e.g., one week) and the purpose of this constant is to minimize any long term bias in
15 the measurement of the U-235 weight.

In an example use of the method of the invention the fuel element was clad with zirconium alloy tubing with an outside diameter of about 1.3 cm and a wall thickness of about
20 0.8 mm and containing a column of fuel pellets about 3.5 m in length. The fuel was arranged in the fuel element in 7 zones of different length and different enrichment and gadolinium content. The fuel element was
25 driven past the gamma ray detectors at a velocity of 1.5 feet per minute and readings were taken from the pulse counters at a sampling rate of 3 samples/second. The results of a scan of this fuel element are shown
30 in Fig. 3. Accuracy in determination of U-235 content in the fuel element was in the order of plus or minus 0.4 percent (single standard deviation).

While the invention has been described
35 with respect to a particular embodiment of the method and an illustrative arrangment for carrying out the method, variations within the ambit of the invention are possible. For example, correction and processing of the signals
40 from the gamma ray detectors need not await completion of scanning of the fuel element but can begin as soon as the last detector has completed scanning of the first zone.

Since sensing of the cladding wall thick-
45 ness, fuel material density and burnable poison content can take place at a scanning rate substantially greater (e.g., in the order of two to four times) than the gamma ray scanning rate, it is desirable that the wall thickness
50 sensor 22, the density sensor 24 and the burnable poison content sensor 26 be located at a separate scanning station and multiple gamma scanning stations be provided to thus increase the throughput of the system as a
55 whole.

Since the accuracy of U-235 determination is a function of enrichment and scanning speed, it is contemplated that the gamma scanning speed be varied zone-to-zone in pro-
60 portion to the enrichments of the zone. This would not only increase throughput but would provide the same accuracy of U-235 determination for each zone.

Means can also be provided to detect devi-
65 ant pellets within a zone (i.e., pellets of incor-

rect enrichment) by comparing the U-235 gamma ray counts of successive sampling times and detecting changes of predetermined magnitude.
70 While the means for carrying out the method of the invention have been illustrated in functional block diagram form in Fig. 2, it is believed obvious that these functions can be achieved in a variety of well-known ways
75 such as by suitably programmed data processing apparatus.

CLAIMS
1. Method for determining the fissile fuel
80 content of nuclear fuel in a fuel element which may also contain a burnable poison mixed with selected portions of the fuel therein, said fuel element including an elongated cladding tube containing the fuel
85 material, comprising the steps of:

(1) determining a plurality of sequential zone of said fuel material in said fuel element;

(2) detecting the gamma ray emission due to the natural radioactive decay of said fuel
90 material in each of said zones in sequence;

(3) analyzing the gamma ray signals from each of said zones and determining a first gamma ray count of gamma rays within a predetermined range of energies primarily at-
95 tributable to said fissile fuel and determining a second gamma ray count of gamma rays of energy greater than said predetermined range of energies;

(4) determining for each zone the thickness
100 of the cladding adjacent the zone;

(5) correcting said first and second gamma ray counts in accordance with the cladding thickness adjacent each zone;

(6) determining the density of the fuel
105 material in each zone;

(7) further correcting said first and second gamma ray counts in accordance with the density of the fuel material in the zone;

(8) determining the weight percent of bur-
110 nable poison in each of the zones;

(9) further correcting said first and second gamma ray counts for each zone in accordance with the weight percent of burnable poison in the zone;
115 (10) further correcting said first gamma ray count in accordance with the corrected second gamma ray count; and

(11) determining from the thus corrected first gamma ray count the weight percent of
120 fissile fuel in each zone.

2. The method of claim 1 further including the step of determining from the weight percent of fissile fuel, the weight percent of burnable poison and the density of fuel
125 material in said zones and from the volumes of the fuel material in the zones the weight of fissile material in each of said zones.

3. The method of claims 1 or 2 wherein said zones are determined from the distribu-
130 tion of burnable poison along the length of

said fuel element.

4. The method of claims 1–3 wherein said fissile fuel is U-235 and said nuclear fuel is uranium fuel.

5. The method of claim 4 further including the step of determining from the weight percent of U-235, the content of burnable poison and the density of the fuel material in said zones and from the volumes of said fuel material in the zones the weight of U-235 in each of said zones.

6. Method for determining the U-235 content of uranium fuel in a fuel element which also may contain gadolinium as a burnable poison mixed with selected portions of the fuel therein, said fuel element including an elongated cladding tube containing the fuel material, comprising the steps of:

(1) determining a plurality of sequential zones of said fuel material along the length of said fuel element;

(2) detecting the gamma ray emission due to the natural radioactive decay of said fuel material in each of said zones in sequence;

(3) analyzing the gamma ray signals from each of said zones and determining a first gamma ray count of gamma rays of energy in the range of from about 155 to about 220 Kev and determining a second gamma ray count of gamma rays of energy in the range of from about 245 to about 1190 Kev;

(4) determining for each zone the thickness of the cladding at the zone;

(5) correcting said first gamma ray count in accordance with:

$$Aw = \frac{Ar}{_eK_1dw} \quad where$$

Aw is said first count corrected for cladding wall thickness,

Ar is the uncorrected first count,

e is the base of the natural system of logarithms,

dw is the deviation of the wall thickness from design value, and

K_1 is a wall thickness correction constant;

(6) correcting said second gamma ray count in accordance with:

$$Bw = \frac{Br}{_eK_4dw} \quad where$$

Bw is said second count corrected for cladding wall thickness,

Br is the uncorrected second count, and

K_4 is a wall thickness correction constant;

(7) determining the density of the fuel material in each zone;

(8) further correcting said first gamma ray count in accordance with:

$$Awd = \frac{Aw}{1 + K_2dd} \quad where$$

Awd is said first count corrected for cladding wall thickness and fuel material density,

dd is the deviation of the fuel material density from design value, and

K_2 is a density correction constant;

(9) further correcting said second gamma ray count in accordance with:

$$Bwd = \frac{Bw}{1 + K_5dd} \quad where$$

Bwd is said second count corrected for cladding wall thickness and fuel material density, and

K_5 is a density correction constant;

(10) determining the gadolinium content in each of the zones;

(11) further correcting said first gamma ray count in accordance with:

$$Awdp = \frac{Awd}{1 + K_3dp} \quad where$$

Awdp is said first count corrected for cladding wall thickness, fuel material density and gadolinium content,

dp is the deviation of gadolinium content from design value, and

K_3 is a gadolinium content correction constant;

(12) further correcting said second gamma ray count in accordance with:

$$Bwdp = \frac{Bwd}{1 + K_6dp} \quad where$$

Bwdp is said second count corrected for cladding wall thickness, fuel material density and gadolinium content, and

K_6 is a gadolinium content correction constant; and

(13) further correcting said first gamma ray count in accordance with:

$$Ac = Awdp - K_7Bwdp \quad where$$

Ac is the finally corrected first gamma ray count, and

K_7 is a correction constant associated with said second gamma ray count.

7. The method of claim 6 further including the step of determining the enrichment of U-235 in each zone in accordance with:

$$Ae = K_8Ac + K_9 \quad where$$

Ae is the average enrichment in the zone in

weight percent, and

K_8 and K_9 are enrichment calibration constants.

8. The method of claim 7 further includ-
5 ing the step of determining the weight of U-235 in each zone in accordance with:

$$Awt = K_{10} \, Ae \, dm \, Lz \, (1 - .01 \, Pw)$$
$$(10.95 - .034 \, Pw) + K_{11}$$

10
where

Awt is the weight of U-235 in the zone,

dm is the measured density of the fuel
material in the zone in percent of theoretical
15 density,

Lz is the length of the zone,

Pw is the weight percent of gadolinium in
the zone,

K_{10} is a conversion constant,
20 K_{11} is a constant which accounts for bias in
measurements compared to known standards.

term .01 is a factor for conversion of weight
percent to weight fraction,

term 10.95 represents the density of fuel
25 pellets without burnable poison, and

term .034 represents the change in pellet
density due to one percent burnable poison
content.

9. The method of claim 8 wherein the
30 lengths of said zones are determined from the
changes in gadolinium content along the
length of said fuel element.

10. A method for determining fissile fuel
content of a nuclear fuel in a fuel element as
35 claimed in claim 1 substantially as hereinbe-
fore described with reference to and as illus-
trated in the accompanying drawings.