Reports

A Model for Plate Tectonic Evolution of Mantle Layers

Abstract. *In plate tectonic theory, lithosphere that descends into the mantle has a largely derivative composition, because it is produced as a refractory residue by partial melting, and cannot be resorbed readily by the parent mantle. We suggest that lithosphere sinks through the asthenosphere, or outer mantle, and accumulates progressively beneath to form an accretionary mesosphere, or inner mantle. According to this model, there is an irreversible physicochemical evolution of the mantle and its layers. We make the key assumption that the rate at which mass has been transferred from the lithosphere to the mesosphere is proportional to the rate of radiogenic heat production. Calculations of mass transfer with time demonstrate that the entire mass of the present mesosphere could have been produced in geologically reasonable times (3×10^9 to 4.5×10^9 years). The model is consistent with the generation of the continental crust during the last 3×10^9 years and predicts an end to plate tectonic behavior within the next 10^9 years.*

In the specific version of plate tectonic theory called by its authors "the new global tectonics" (*1*), rigid surficial plates of lithosphere move about with respect to one another and locally descend into the asthenosphere, an underlying medium with less strength. We assume that the plates of lithosphere are composed in large part of refractory material, probably peridotite, representing mantle depleted by extraction of a low-melting fraction during partial melting that occurs mainly beneath oceanic rises. The basaltic melts produced ascend to rise crests where they build oceanic crust as a relatively thin layer on top of the depleted mantle. The eventual fate of lithosphere that has descended into the asthenosphere is the most important petrologic question posed by plate tectonic theory.

The positions of descending slabs of lithosphere are marked by inclined seismic zones that dip beneath the magmatic arcs of arc-trench systems. The seismic foci probably occur mainly within the slabs, which act as stress guides (*2*). None of the inclined seismic zones extend to depths exceeding 700 km, some cannot be identified below depths of 250 to 300 km, and others have pronounced gaps in seismicity between depths of 250 and 500 km (*3*). Solutions indicating focal mechanisms (*3*) for earthquakes along planar, inclined seismic zones suggest different stress orientations in different slabs or parts of slabs: (i) where seismicity does not extend below 250 km, stresses oriented along the dip in the slabs are apparently extensional, as if the slabs were hanging downward into a medium of lower strength [Elsasser (*3a*) has recently noted that it would be more correct to speak of this "weak" layer in terms of greater "softness," rather than lesser "strength"]; (ii) where seismicity extends continuously from the surface to depths in excess of 500 km, stresses oriented along the dip in the slabs are apparently compressional, as if the slabs had struck a layer of increased strength at the bottom of their descent; (iii) where there is a prominent gap in seismicity between 250 and 500 km, earthquakes above 250 km imply extensional stresses, as in the first case, whereas earthquakes below 500 km imply compressional stresses, as in the second case.

We conclude that the asthenosphere extends from the top of the low-velocity zone at a depth of about 70 km (*4*) to the level of the deepest earthquakes near 700 km. The material below the asthenosphere and comprising the rest of the mantle is termed the mesosphere (*1*). The top of the mesosphere is thus approximately the base of the outer mantle as defined by a discontinuity in seismic velocity near 620 km or slightly deeper (*5*). We adopt here the compromise figure of 650 km as the depth to the top of the mesosphere, which we identify as the inner mantle.

When lithosphere descends into the asthenosphere, the portion of it representing a depleted residue from partial fusion probably never returns to shallow levels but rather displaces upward relatively unfractionated material to serve as a source for the production of more lithosphere along rise crests (*6*). We can imagine no effective mechanism for dispersing depleted, residual materials of the lithosphere back into undepleted, parent materials of the deeper mantle. We suggest, therefore, that descending lithosphere is added progressively to the outer surface of the mesosphere. The total bulk of the mesosphere was thus built outward from the core boundary by the accumulation of successive increments of lithosphere, and the mass of the mesosphere has increased through time at the expense of the asthenosphere. This model implies an irreversible plate tectonic evolution of the layers of the mantle. We shall discuss below other, less attractive possibilities for the disposal of lithosphere, but now we shall evaluate this evolutionary model in terms of the overall mass transfer rates required.

Available data permit estimates of the present mass transfer rate, within limits. The amount of lithosphere consumed must equal the amount of lithosphere produced for time periods during which the earth's size does not change. From the pattern of magnetic anomalies on the sea floor (*7*), we estimate that lithosphere equal in area to approximately half the ocean basins, or about 30 percent of the earth's surface, has been formed in the last 75×10^6 years. Vine (*8*) inferred that the same area of sea floor formed slightly faster, within the last 65×10^6 years. Elsas-

Table 1. Tabulated estimates of the present (0 to 10^8 years) mass transfer rate (R_m) of material from the surficial lithosphere to the mesosphere, expressed as 10^{16} g/year with the assumption that the mean density of the lithosphere is 3.25 g/cm^3. The asterisk denotes our best estimate.

Effective thickness (d) of lithosphere (km)	Areal rate (R_A) of consumption of lithosphere (in km^2/year = 10^{10} cm^2/year)		
	1.7	2.0	2.3
15	8.3	9.75	11.2
50	27.6	32.5*	37.4
100	55.3	65.0	74.7

ser (*9*) estimated that roughly half the whole lithosphere has been replaced in the last 150×10^6 years. These figures indicate that lithosphere has been produced and consumed at an areal rate of 1.7 to 2.3 km²/year during the past approximately 10^8 years. Our best estimate is 2.0 km²/year, a rate sufficient to have produced all the present ocean basins since the Late Jurassic, which is widely quoted as the oldest horizon present in most oceans (*10*).

The present rate of mass transfer from surficial lithosphere to the mesosphere can be derived from the areal rate of production and consumption of lithosphere by estimating the effective thickness and mean density of the descending slabs. The figure of 100 km initially suggested (*11*) for the approximate thickness of oceanic lithosphere will be considered here as a maximum value. A more probable figure of 50 km (*12*) is adopted here as a medial value. The minimum figure, in terms of our hypothesis, is the net thickness of residual mantle, depleted of its lower melting fractions by extraction of the oceanic crust. For 30 percent partial melting, which would seem to be near the maximum proportion conceivable for a mantle of pyrolitic composition (*6*), the depleted material would be about 15 km thick in aggregate. Lesser proportions of partial melting would correspond to greater effective thicknesses of depleted mantle in the lithosphere, and our medial figure of 50 km would, in these terms, correspond to 10 percent partial melting. Using three alternate figures (15, 50, and 100 km) for the effective thickness of sinking lithosphere, and assuming for it a mean density of 3.25 g/cm³, we list mass transfer rates that correspond to the previously estimated areal consumption rates (1.7, 2.0, and 2.3 km²/year) for the last 10^8 years in Table 1.

Past rates of mass transfer can be calculated if it is assumed that past rates have varied, as a first approximation, in direct proportion to the rates of production of radiogenic heat within the earth. We justify this assumption on the basis that plate tectonic motions presumably constitute a convective system (*9*). Of the several earth models available, we have selected three for an evaluation of the production of radiogenic heat through time. Lubimova (*13*) discussed the heat production by terrestrial radioisotopes during geological time with respect to the three models considered: (i) the chondrite model (*14*), (ii) the model for carbonaceous chondrite or the Orgueil meteorite (*15*), and (iii) the model of Wasserburg *et al.* (*16*) based on K/U and Th/U ratios actually observed in terrestrial materials. Using these three models, we have calculated the rate of heat production as a function of time and have determined ratios of heat production as various times in the past to that at present. Numerical constants used in the calculations are given in detail in Tables 2 and 3. Figure 1 shows the ratio of the rates of production of radiogenic heat (Q_R) in the past to that at present for each of the three earth models as a function of time. The scale at the right of Fig. 1 gives the corresponding rates of mass transfer (R_m) implied for the past by our best estimate for R_m at present (see Table 1).

We use rates of mass transfer derived in this fashion to calculate how long the descent of slabs of lithosphere must have continued in order to develop the full mass of the current mesosphere (Fig. 2). Inferred rates of mass transfer at various times in the past are directly related to the rate effective at present by the curves of Fig. 1. Consequently, Fig. 2 is plotted in terms of the present rate of mass transfer versus the time in the past at which accretionary growth of the mesosphere must have begun if our various assumptions are valid. The results are shown for each of the three earth models considered. For example, if accretionary growth of the mesosphere began 3.25×10^9 years ago in a "chondritic" earth, the radiogenic heat produced through time according to this model (see Fig. 1) would be consistent with a mass transfer rate at present of 43.5×10^{16} g/year, a figure near the best estimate of Table 1. The current mass transfer rates shown are converted at the right of Fig. 2 to effective thicknesses (d) of descending slabs of lithosphere at present as a function of the present areal rates (R_A) of consumption of surficial plates of lithosphere for two assumed mean densities (ρ), where

$$R_m = \rho d R_A$$

The preceding analysis is a presumptive test of our working hypothesis. Figure 2 indicates that the mass of the mesosphere between the depths of 650 and 2900 km could have been produced within a geologically reasonable time span by the accretionary addition of descending lithosphere to its growing outer surface. All three of the earth models considered permit this conclusion, provided we are approximately correct in our key assumption that the rates of mass transfer of lithosphere moving downward through the asthenosphere have been directly proportional to the rates of production of radiogenic heat within the earth. Our best estimate (2 km²/year) for the current areal rate of consumption of surficial lithosphere, when coupled with our medial estimate (50 km) for the effective thickness of surficial plates and descending slabs of lithosphere at present, provides remark-

Table 2. Values of Q_P, the radiogenic heat production at the present (in ergs per gram per year), and λ, the decay constant for the three earth models. Values for Q_P are those of Lubimova (*13*). The equation used in the calculation of heat production is given in Table 3.

Model	Parameter	Isotope			
		^{238}U	^{235}U	^{232}Th	^{40}K
Chondrite (*14*)	$Q_P \times 10^1$	5.6	0.3	4.9	12.8
Orgueil (*15*)	$Q_P \times 10^1$	13.9	0.6	10.0	6.3
Wasserburg (*16*)	$Q_P \times 10^1$	9.8	0.4	10.2	3.5
	$\lambda \times 10^{10}$	1.54	9.72	0.499	5.30

Table 3. Numerical constants and equations.

For each isotopic decay scheme:

$$Q_t = Q_P e^{\lambda t}$$

where Q_t is the radiogenic heat production at time t in the past (in ergs per gram per year), Q_P is the radiogenic heat production at the present, and λ is the decay constant (values of Q_P and λ used in this calculation are listed in Table 2).

Density of the present-day mesosphere calculated on the basis of a linear estimate from Press (*17*):

$$\rho = 7.414 - 5.5 \times 10^{-4}\, r$$

where r is the radius in kilometers.

Mean density of the lithosphere: 3.25 g/cm³

Radius of the earth: 6371 km

Depth to core-mantle boundary: 2900 km

Mass of the present-day mesosphere: 2.92×10^{27} g able agreement with both the Wasserburg model and the Orgueil model if the accretionary process began about 4.5×10^9 years ago, near the time when the earth was formed. For the chondritic model, the same assumptions would imply that accretion began about 3.75×10^9 years ago, just prior to the formation of the oldest known crustal rocks. We assume that combinations of parameters which predict times much less than about 3×10^9 years are not reasonable because of inferred rates of continental growth, a process which we relate to plate tectonic theory (see below).

Our reliance in this analysis on transfer rates for mass is intended to bypass crucial problems related to the thermal history of the earth. Changing temperatures and densities at various depths as a function of time do not enter into our calculations. In order to determine the total mass of the present mesosphere, we have used the density gradient for the inner mantle given by Press (*17*). Time-dependent variations in the characteristic properties of surficial plates of lithosphere also do not concern us, provided we assume only that the lithosphere at any given time has always been heavy enough to descend at a significant rate through the asthenosphere present at the same time. For the lithosphere, any past combinations of mean density, effective thickness, and areal consumption rate that yield the required mass transfer rates for delivery of material to the growing surface of the mesosphere are acceptable. For example, a past R_m value twice the current value could be reached without change in the effective thickness of lithosphere plates by doubling the areal consumption rate. The same R_m value could be achieved with lithosphere plates only half as thick as the present ones if the areal consumption rate were higher than the current one by a factor of 4. Because the areal consumption rate we have cited here is a globally integrated value, any postulated increase in the rate could be satisfied either (i) by increased rates of spreading and consumption along plate boundaries with the same aggregate length as the present boundaries, or (ii) by an increase in the number and aggregate length of spreading and consuming plate boundaries without change in the characteristic rates of spreading and consumption applicable to a given plate boundary.

We shall now briefly consider alternate means for the disposal of lithosphere that descends into the asthenosphere along the inclined seismic zones. Some or all of the materials in the crustal layers along the upper surfaces of the descending slabs may be removed during descent. Some materials may be scraped physically off the tops of the slabs at the beginning of their descent and added to the growing melange belts associated with trenches. Other materials may be melted at deeper levels beneath the arcs and added to the arc structures or their underpinnings as erupted or intruded magmas. These processes combined are not significant for the disposal of descending lithosphere. If we assume typical rates of plate consumption at trenches, the entire crust of modern arc-trench systems could have been built during the

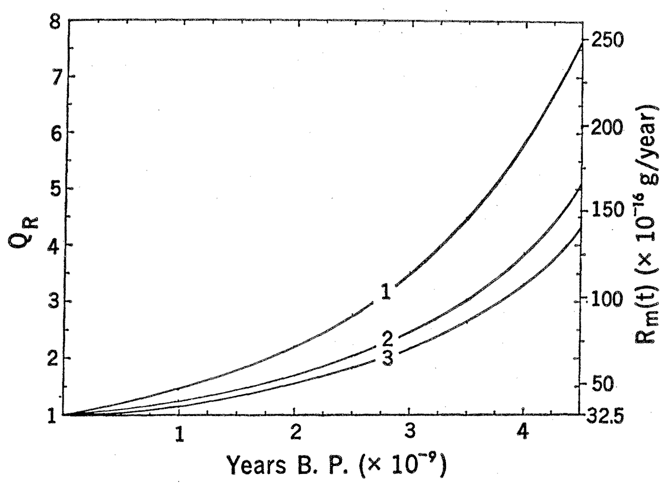

Fig. 1 (left). Relative radiogenic heat production in the past; Q_R is the ratio of heat production at any time in the past to that currently observed. B.P. is time before the present. Values for Q_R were calculated for each of the following earth models: (i) the chondrite model (*14*), curve 1; (ii) the carbonaceous chondrite or Orgueil model (*15*), curve 2; and (iii) the Wasserburg model (*16*) based on K/U and Th/U ratios observed in terrestrial rocks, curve 3. Numerical values used in these calculations are listed in Tables 2 and 3. Values of $R_m(t)$ refer to the rate of mass transfer of lithosphere to mesosphere calculated on the basis of our best estimate given in Table 1.

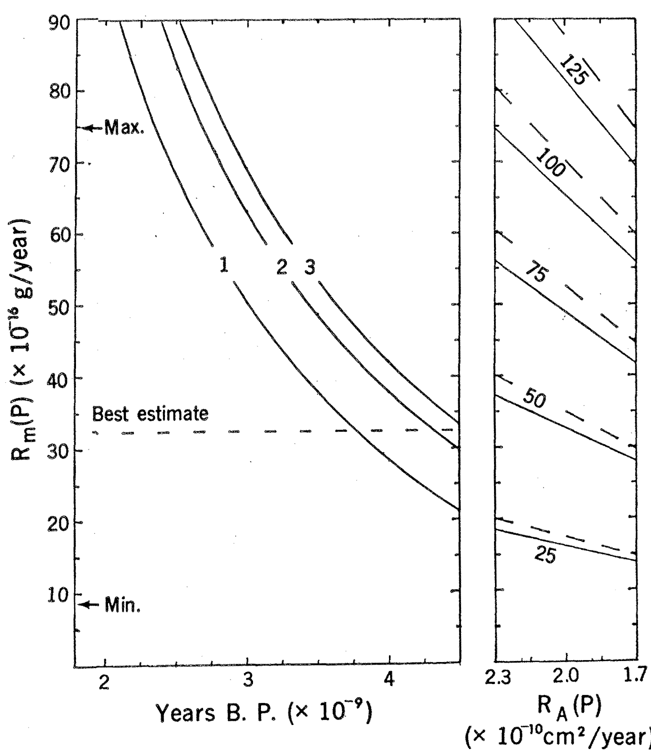

Fig. 2 (right). Calculated mass transfer rates at present, $R_m(P)$, for a mesosphere which began accretionary growth at some time, *t*, in the past. Curves are shown for each of the three earth models of Tables 2 and 3 and Fig. 1. Our best estimate of $R_m(P)$ and the maximum and minimum values for $R_m(P)$ are from Table 1. Lines indicated by numerical values of 125, 100, 75, 50, and 25 refer to present effective plate thicknesses, *d*, and illustrate the relationship of *d* to the present areal consumption rate, $R_A(P)$, and to $R_m(P)$. The solid lines are for an assumed mean density, ρ, of 3.25 g/cm³, and the dashed lines are for a mean density of 3.5 g/cm³ for the present lithosphere. An example of inferences that can be made from the graph is as follows: for an assumed $R_m(P)$ of 56×10^{16} g/year, accretionary growth of the mesosphere could have begun at 2.8×10^9 years B.P. (chondrite model), 3.25×10^9 years B.P. (Orgueil model), or 3.4×10^9 years B.P. (Wasserburg model); present *d* values corresponding to $R_m(P) = 56 \times 10^{16}$ g/year are (i) 75 km for $R_A(P) = 2.3 \times 10^{10}$ cm²/year and $\rho = 3.25$ g/cm³, or $R_A(P) = 2.15 \times 10^{10}$ cm²/year and $\rho = 3.5$ g/cm³, or (ii) 100 km for $R_A(P) = 1.7 \times 10^{10}$ cm²/year and $\rho = 3.25$ g/cm³.

time spans of their known activity with a cumulative contribution of mass equivalent to a thickness of only about 1 km of the moving slabs of lithosphere that have descended beneath them (*18*). Most of the lithosphere that descends into the asthenosphere evidently remains in the mantle in some form.

We discounted above the idea that any portion of the lithosphere representing a refractory residue from partial melting of the asthenosphere can be resorbed effectively by the asthenosphere. We recognize that any portion of the lithosphere which represents instead only chilled, but undepleted, asthenosphere could well be resorbed at depth. We have avoided estimating the relative thicknesses or proportions of these two possible kinds of constituents in the lithosphere by restricting discussion of mass transfer rates of lithosphere to an "effective" thickness, which, in the limiting case, means the thickness of lithosphere representing depleted asthenosphere. It might be supposed that this depleted material need not descend entirely through the asthenosphere but could remain somehow suspended within it as slabs and blocks that would contribute to the inhomogeneity of the outer mantle. This mechanism of disposal cannot account for all the lithosphere that probably has descended into the asthenosphere unless our estimates of the cumulative mass transported downward from the surface during geologic time are high by an order of magnitude. To consider the inclusion of residual pieces of lithosphere within the asthenosphere as a general means of disposal, at least one of two inferences must be made: (i) our estimates of past rates of mass transfer are much too high or (ii) plate tectonic motions have been restricted to a small fraction of geologic time. If the interface between the outer mantle, composed of lithosphere and asthenosphere, and the inner mantle is assumed to be a stable boundary across which mass transfer is prohibited, then both inferences are probably necessary. This condition arises because the proportion of depleted residue included within the asthenosphere must remain low enough to leave the asthenosphere viable as a potential reservoir for the continued extraction of complementary lithosphere and oceanic crust along the rise systems at the present time.

Karig (*19*) has suggested recently that much of the lithosphere that descends beneath island arcs subsequently rises in mantle diapirs associated with the spreading seas that open behind some arcs. For two reasons, we do not think that this suggestion offers a general means for the effective disposal of lithosphere: (i) because some arcs, such as the Andes, lack spreading centers in their rears, and (ii) because the mechanism does not avoid the basic dilemmas posed by the dispersal of lithosphere into the asthenosphere.

We conclude that none of the alternatives for the disposal of lithosphere are more attractive than our model, and we turn now to the salient implications of our model for the growth of continents and the geochemical evolution of the mantle. Two extreme views of continental growth have been held in the past: (i) essentially the whole mass of the continental crust was formed early in the Precambrian, and (ii) the continents have grown throughout Precambrian and Phanerozoic time by incremental additions in the form of successive peripheral orogenic belts. The significance of the well-known continental belts of rocks yielding different radiometric ages is interpreted differently from the two points of view. In the static view, the radiometric age belts record fundamentally metamorphic events including sedimentary recycling and anatectic reworking of continental substance (*20*). In the evolutionary view, the radiometric age belts record fundamentally igneous events by which new continental substance emerges from the mantle (*21*). We accept the latter view, which can be related closely to plate tectonic theory through the hypothesis that continental crust is formed in arc-trench systems at convergent plate junctures (*18*). Whatever the details of the process, the generation of continental crust in arc-trench systems must be some function of the rate of descent of lithosphere in these regions. For this reason, the rate of continental growth must be an integral facet of our overall hypothesis for the disposal of lithosphere.

Continental rocks yielding radiometric dates older than about 2.75×10^9 years are rare, although they do occur at isolated localities in the interior of nearly every shield area on each continent (*22*). Although we are aware of the severe problem posed by metamorphism that has reset radiometric clocks in all but a few relics of these most ancient continental nuclei, we tentatively accept the scarcity of dates prior to 2.75×10^9 years ago as evidence that most continental crust was formed later. Earlier workers (*23*), who accepted the accretionary model of continental evolution for North America, concluded that the areal rate of growth has been roughly uniform during the past 2.75×10^9 years. We affirm this result, using more recent data compiled by King (*24*), and note further that the apparent growth rate is sufficient to form all of North America in roughly the past 3×10^9 years. If there is significant bias in the data, it involves an overemphasis on the area of younger radiometric belts at the expense of older belts whose original radiometric ages are partly masked by younger metamorphic events. The data for North America are probably representative for all the continents taken together as a group (*22*).

A rather even rate of continental growth over the past 2.75×10^9 years, with perhaps slightly higher growth rates in the earlier part of that period, implies by our reasoning a semiconstant mass transfer rate for lithosphere moving from the surface to the mesosphere during that time span. The mass transfer rates inferred in Fig. 1 do vary exponentially with time, but the rate inferred for 2.75×10^9 years ago is no more than two to three times the present rate. If most of the continental masses have indeed formed during the past 3×10^9 years, some discontinuity in the behavior of the mantle at that time is implied. The data suggest two possibilities for the nature of this discontinuity: (i) the plate tectonic system involving the transfer of lithosphere from the surface to the mesosphere may have begun acting at about that time [this hypothesis is consistent with our model only in terms of our highest reasonable estimates of the effective thickness of the present plates of lithosphere (see Fig. 2 and Table 1)]; (ii) the high mass transfer rates prior to 3×10^9 years ago (see Fig. 1) may have been associated with an overall heat flux high enough to make the petrologic expression of the plate tectonic system qualitatively different, such that continental crust as we know it did not begin to aggregate until later. Operation of the plate tectonic system prior to 3×10^9 years ago is implied by our medial and lower estimates of present mass transfer rates (see Fig. 2). Transfer of lithosphere downward prior to 3×10^9 years ago may have been associated with a sort of protoplate tectonics involving subduction in diffuse patterns, whereas the true continental shields of permanent aspect and the rigid oceanic slabs of true plate tectonics date only from about 2.75×10^9 years ago.

In the foregoing discussion, we ignore the possibility of a worldwide cyclicity in the process of continental accretion (*25*). Demonstration of undoubted cyclicity of this kind would logically force refinement of estimates of our mass transfer rates for the past to fit some cyclic pattern. We note also that a detailed consideration of the geochemical evolution of the mantle may ultimately suggest other refinements in our model. The most obvious implication of the model in this context is the inference that the composition of the present lithosphere is a key to the composition of the inner mantle. A second logical consequence of the proposed model is that the material of the asthenosphere, rather than the mesosphere, most closely approximates a primitive composition.

Our hypothesis of sinking lithosphere, accretionary mesosphere, and shrinking asthenosphere is a dynamic model for the irreversible evolution of the entire mantle at a rate linked to the rate of production of radiogenic heat in the earth. Appropriate assumptions produce a viable semiquantitative model in terms of the mass transfer required within the time available and also are in reasonable accord with corollary inferences about the growth of continents. No physicochemical details have been treated, as our intent has been to test the overall model to a first approximation. Simple extrapolation of the assumptions we have made for the past into the future indicates that an earth lacking asthenosphere and presumably incapable of plate tectonic behavior as we now know it will be produced in less than 10^9 years. It is conceivable to us that apparently "dead" planetary bodies, like the moon and Mars, may have reached such a state by completing an internal evolution similar to the one that we suggest is now in progress in the earth's mantle.

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Hyperfine Zeeman Effect Atomic Absorption Spectrometer for Mercury

Abstract. *A new type of atomic absorption spectrometer—one that detects trace mercury in host material, based on hyperfine structure lines in a magnetic field—was developed and tested on various substances. This device can detect trace mercury to about 0.04 part per million (40 parts per billion) in about 1 minute. No chemical separation from the host material is necessary.*

A problem of importance today is the detection of mercury in food, especially in fish such as tuna and swordfish. Unfortunately, as far as we know, no device available yields a rapid determination of mercury to about 0.1 ppm in about 1 minute without preliminary separation of the mercury from the host material. Because of the urgent need for the detection of mercury, we have converted to this purpose a mercury optical-pumping nuclear magnetic resonance magnetometer (*1*) which we had contructed to measure magnetic fields. We were motivated to use this technique because we can observe routinely in our magnetometer a magnetic resonance signal whose equivalent density is about 10^{10} to 10^{11} atoms per cubic centimeter. This corresponds to about 10^{-12} g of mercury per cubic centimeter. Because of the intrinsic power of detection of this apparatus and because considerable work had been done to construct a stable, intense, sharp mercury lamp and associated electronic equipment, we believed that converting the magnetometer to a mercury detector would be useful.

Our objective was to develop an instrument that can be operated by completely inexperienced personnel (such as fishermen), has high accuracy in mercury detection to at least 0.04 ppm (40 ppb), is very rapid in analysis without any chemical separation from the host material, and is inexpensive. We believe that our prototype instrument satisfies the above aims, although the unit in its present form is not quite

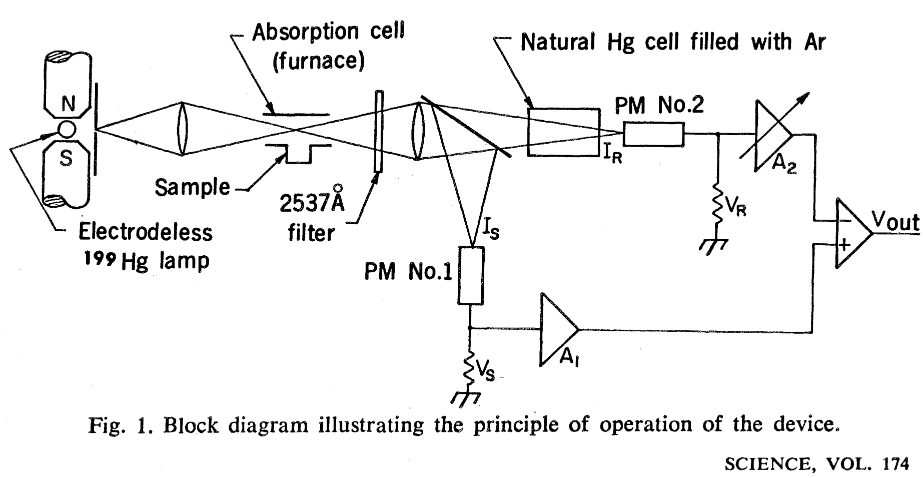

Fig. 1. Block diagram illustrating the principle of operation of the device.