Editor's Note: *This is the forty-ninth in a series of review and tutorial papers on various aspects of acoustics.*

The notebooks of Wallace C. Sabine

Leo L. Beranek

Bolt Beranek and Newman Incorporated, Cambridge, Massachusetts 02138
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Generally believed lost, 12 of Wallace Clement Sabine's notebooks have been offered by the Riverbank Laboratories, IITRI, of Geneva, Illinois, to Harvard's rare books library for safekeeping. The author has indexed the notebooks against Sabine's published papers and has sought an answer to Sabine's silence in the 1900–1904 period following the opening of Boston Symphony Hall. The investigation reveals that all significant data recorded in the notebooks were either submitted for publication prior to 1915 or were taken in 1915 just before Sabine became involved in World War I scientific service abroad. He died in January 1919. The excising of over 200 pages from his notebooks just after 1900 indicates that he may have been disappointed in his predictions of the reverberation times of Symphony Hall. This paper summarizes the contents of the notebooks and explains the reason for the discrepancy between his predictions and more recent measured reverberation times for Symphony Hall. It portrays the depth of Sabine's experimentation, his influence on the growth of applied physics at Harvard, his extensive consultation with architects, and his service in the war effort.

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INTRODUCTION

In 1939, Professor Theodore Lyman, Harvard University's famous physicist, was reminiscing about Wallace Clement Sabine. He told me that he had seen Sabine one day outside the Jefferson Physical Laboratory burning his research papers. On questioning him Lyman thought that Sabine seemed to be in a state of depression about his work in acoustics. In his introduction to Sabine's papers,[3] Lyman wrote in June 1921, "It is a melancholy fact that these papers [Lyman is commenting on certain technical material referred to in Sabine's published works] were either never written or else were destroyed by their author; no trace of them can be found. ... The severity of the criticism which Professor Sabine always applied to his own productions increased with time, and it is to this extreme self-criticism and repression that we must ascribe the loss of much invaluable scientific material."

With this background, I was startled when Ralph Huntley told me in April 1975 that he had examined some notebooks at the Riverbank Acoustical Laboratories in Geneva, Illinois, which he was sure were those of Sabine. I immediately wrote to the Directors of the Riverbank Laboratories, offering to index the notebooks and suggesting that they be deposited for preservation in the Harvard University Archives. In September they arrived—12 notebooks "in the field of acoustics, reverberation, and transmission to be presented to Harvard University Archives for reference and preservation." Imagine my eagerness to learn how Sabine had approached his work, what he thought of his acoustical masterpiece, Boston Symphony Hall, and whether he had indeed kept much of the record that Professor Lyman believed had been destroyed!

I. DESCRIPTION OF THE NOTEBOOKS

The 12 notebooks are identical in appearance, with hard covers bound in imitation black buckram with red reinforced corners and spine. They were purchased from "H. C. S." (Harvard Cooperative Society) and are in two thicknesses, size 2 with 152 pages and size 3 with 218 pages. Some of them are marked either 40 or 60 cents, depending on size, and they were apparently from two different lots. Each page is machine numbered and is ruled in 5×5 mm squares. Sabine wrote mostly in pencil, occasionally in ink, in neat, clear script and numbers. He generally used the odd-numbered pages for data and the even-numbered ones for analysis, summary, and comment. Unfortunately, in some of the books he dated his work only occasionally so that some dates have to be deduced from jottings like "the day Orville Wright was badly hurt," or from dates given in his published papers or his mother's diary.[4]

Each book has a typed gummed label with a serial number on the upper spine and a larger gummed label on the cover with a brief typed list of contents. They were apparently labeled and numbered at the same time, perhaps after his death since the numbers assigned to the notebooks do not correspond to the order in which they were written (see Table I). As evidenced by the contents and printing details, those numbered 1 to 7 were bought prior to 1900.

Many pages have been removed. A few were removed here and there apparently to eliminate material with which Sabine was dissatisfied. In seven of the books a large number of pages were cut out with a sharp knife starting on page 1 through the page number indicated in column 4 of Table I.

An interesting and typical page of Notebook 7 is reproduced in Fig. 1 to show Sabine's style and attention to detail. A brief summary of the contents of the notebooks follows:

A. Book 1

Using three observers (LeClear, Dinsmore, and himself) Sabine studied Sanders Theatre, four rooms in the Jefferson Physical Laboratory, rooms 1, 15, 41, and the Constant Temperature Room, three rooms in the Botanical Laboratories, the Lecture Hall in the

TABLE I. Periods covered by Sabine's 12 Notebooks.

Dates covered	Notebook number	Pages	Pages missing	Comments
3 December 1898–July 1899	1	1–215	...	This book records a year of further studies after Sabine was commissioned as acoustical consultant for Boston Symphony Hall.
27 October 1899–May 1900	4	1–63	...	The first 63 pages follow Book 1 directly. The remaining pages follow Book 8.
January 1899–Spring 1900	7	1–136	...	Contains a complete review of all data from 12 July 1896, including those data in Books 1 and 4. New data are interspersed, all data at 512 Hz only.
		No Record Spring 1900–*Summer* 1904		
Summer 1904	6	29–204	1–28	First test using 16 organ pipes to produce a wide range of frequencies.
Summer 1904–August 1905	2	107–200	1–106	Measurements on felt, audience, settees, and chairs at seven frequencies.
8 August–Fall 1905	5	95–128	1–94	Best audience data. Lunchroom data on hard-pine sheathing. Measurement on "Sense of Loudness" at six frequencies.
Fall–Winter 1905	3	31–210	1–30	Extensive data on hair felt at various thicknesses and places in the test room at seven frequencies.
		No Record 1906–*Summer* 1908		
Summer 1908–April 1909	8	1–150	...	Consulting projects and fees.
		No Record May 1909–*Early Summer* 1914		
Early Summer 1914	4	67–197	...	First indication of measurements of sound transmission loss (TL).
Summer 1914	11	89–142	1–88	Measurement of TL. These data are basic to Reference 8, Sabine's last paper.
10 February–15 April 1915	9	119–164	1–118	TL data on many structures. Never published.
29 April–10 May 1915	10	109–119	1–108	Some unpublished TL data.
15 May–30 June 1915	12	1–63	...	Much unpublished TL data.
		No Record July 1915–*Fall* 1918		
Fall 1918–8 January 1919	12	65–67	...	Standardization of Riverbank Laboratories organ pipes.

Fogg Art Museum, and several rooms in University Hall. His goal was to determine curves of reverberation time at 512 Hz as a function of various lengths of Sanders seat cushions, which he brought into the test rooms for the observations. Sabine also measured the absorption of open windows in rooms Jefferson 1, 15, and 41 and found that 1 m^2 of seat cushion equaled 0.82 m^2 of open window.

From those data he obtained hyperbolic curves for the various rooms and preliminary values for the constant in his reverberation equation. Sabine studied the effect of source power on the length of audible decaying residual sound, and he standardized a factor of 10^6 decrease in intensity (60 dB) as the basis for determining reverberation time. He found that different observers measured nearly the same reverberation times in a given room, and that the position of an observer did not have a significant effect on the results. Data were collected on the sound absorption of plaster walls, chairs, oil paintings, glass, green plants, and rugs. Book 1 ends with calculations of the volumes and areas

On the absorbing power of an audience. After an evening lecture July 24 1899 to the Summer School in the Large Lecture room of the Jefferson Physical Laboratory, on "wireless telegraphy" the audience was requested to remain and the duration of the residual sound determined. The standard pipe was used, tank loaded with six kilograms. and during the test the three rear windows were for the sake of ventilation left open 0.90, 0.70 and 0.50 meters. The audience was extremely quiet and the experiment seemed very successful. There were 138 men, and 157 women, total 295, in the room during the first experiment. One half were then dismissed and the other half asked to remain 79 men and 63 women, total 142. These counts include observers of whom there were three W.C.S. J.L.C. and E.D.D. at chronographs 1, 2, 3, respectively. The following results were obtained.

	room full	room half full	room empty except for these observers. All the apparatus and windows remained exactly as with the audience present
W.C.S.	1.22	1.87	3.57
J.L.C.	1.30	1.92	3.77
E.D.D.	1.44	2.02	3.72
	$1.32 = t_3$	$1.94 = t_2$	$3.69 = t_1$

$a t_1 = .171\ V = .171 \times 1630$

$a t_1 = 279.$ $\qquad a = \dfrac{279}{t_1} = 76.$

$t_2(a + x_1) = 279$

$t_3(a + x_2) = 279$ $\qquad x_1 = \dfrac{279.-147.}{1.94} = \dfrac{132}{1.94} = 68. \qquad \dfrac{68.}{142} = .0.48$

$x_2 = \dfrac{279-100.}{1.32} = \dfrac{179}{132} = 136. \qquad \dfrac{136}{292} = 0.466$

If the calculation is made for each observer in each case the following results are obtained:

$x = 279.\ \dfrac{t_1 - t_2}{t_1 t_2}$

W.C.S	3.57	1.87	1.22	$x_1 = 71.$ $\quad 71 \div 142 =$	0.50
				$x_2 = 150.$ $\quad 150 \div 292 =$	0.51
J.L.C.	3.77	1.92	1.30	$x_1 = 71.$	= 0.50
				$x_2 = 138$	= 0.47
E.D.D.	3.72*	2.02	1.44	$x_1 = 63.$	= 0.44
				$x_2 = 118.$	= 0.41

*During the taking of this record the rubber valve of Mr Densmore's chronograph blew out and but few records were obtained. Its value lower than the reading by Mr LeClear is contrary to the almost universal result. This was determined on a subsequent night under exactly similar conditions to be

FIG. 1. A typical page of Notebook 7, showing Sabine's style and attention to detail.

of the old Boston Music Hall and of Sanders Theatre and gives a first draft of Part III of his monumental 1900 paper.[2]

B. Book 2

The first 106 pages of Book 2 are missing. Intact are data taken in 1904–1905. Most of the data were taken at seven frequencies and have to do with measurements of sound absorption coefficients for seat cushions, felts of various thicknesses and at various spacings from a hard surface, and painted and unpainted brick walls. The total sound absorption is also measured for individual chairs and settees.

C. Book 3

This book contains sound-absorption data at seven frequencies taken in the Constant Temperature Room (CTR), in the Jefferson Physical Laboratory, with and without painted walls, and for one to six layers of felt in one to six places in the rooms. Using ten observers, Sabine measured an equal loudness curve at seven frequencies (octaves from 64 to 4096 Hz) by varying the number of organ pipes at each frequency in order to change the intensity.

D. Book 4

The first 63 pages deal with the effect of varying the intensity on reverberation time measurements at 512 Hz, using one to 16 organ pipes as a source of sound. Absorption coefficients were measured for carpets, cheesecloth, cretonne cloth, cork, open windows, and seats. The remaining 130 pages follow Book 8. They start off with a draft of the introduction to Sabine's 1915 paper on "Insulation of Sound"[8] and include more tests on one to six thicknesses of felt measured at one to six places in the test laboratory. Those pages also include data taken on open windows and on an audience at nine frequencies using ten observers.

E. Book 5

This book contains Sabine's best experiment on the sound absorption of an audience, conducted on 8 August 1905, using eight observers and measurements at six frequencies (512 Hz was not repeated). Book 5 also contains tests conducted in McNamee's lunchroom in Harvard Square, designed to determine the sound-absorption coefficient of hard pine sheathing. Preliminary data are included on the equal loudness contour of Book 3. Some retesting of settees and audience absorption is also recorded.

F. Book 6

This book contains odds and ends of data taken prior to Book 2. Much has been crossed out. More open-window data are taken at seven frequencies in Jefferson 1.

G. Book 7

This book provides the entire basis for the 1898 and 1900 papers titled "Architectural Acoustics."[1,2] It reviews Sabine's work from 12 July 1896 to late 1899. Sabine records, "In order to test the hyperbolic variation of the duration of the residual sound in a room with variation of absorbing material, the work of 1896 is collected, tabulated and plotted. ... This work has all been tabulated here, one page devoted to each room." Some earlier material that appears in Books 1 and 4 is repeated here. Sabine gives summary sound-absorption data, all at 512 Hz, on cement, brick, glass, rugs, open windows, oil paintings, seat cushions, hard pine sheathing, chairs, settees, felt, audience, and plaster, and determines the effect of source power on measured reverberation times. Book 7 ends with calculations for the Leipzig Gewandhaus, the Old Boston Music Hall, and the projected Boston Symphony Hall. The derivation of the "Exact Solution" (Part V of Ref. 2) is also presented here.

Book 7 confirms the great care Sabine used in taking data, and the devotion he recieved from his laboratory assistants, Gifford LeClear and Edward D. Dinsmore. To obtain sufficient quiet for the measurements, his biographer writes that they worked from 11 p.m. to 5 a.m., on three consecutive or alternate nights each week for nearly three years.[4]

H. Book 8

This notebook follows Book 3 and contains calculations on a number of Sabine's consulting jobs, including Union Theological Seminary in New York, Thompson Memorial Chapel at Williams College, St. Mark's Church in Minneapolis, Hall of the House of Representatives in Washington, D.C., Court Room of Penobscot County, Bangor, Maine, and the Hall and Chapel at Haverford College. A schedule of his fees is of interest:

Consulting Fees
(Apparently the academic year 1908–1909)

House of Representatives, Washington, D.C.	$ 500
Middlesex, Massachusetts, Court House	150
Bangor, Main, Court Room	150 + $206.95 expenses
Boston Opera House	200
Union Theological Seminary, New York City	200
St. Mark's Church, Minneapolis	200
Gate of Heaven Organ	100
Ethical Society, Kohn	200
Simpson Memorial	200
Haverford College	200
Columbia University	200
Lynn, Massachusetts	200
Hartford	200
	$2700

Parenthetically, Sabine's salary for this year was $4000 for his professorship and $500 for serving as Dean.

I. Book 9

This book contains the results of a large program to determine the transmission loss of wall structures.

All experiments were performed in the Constant Temperature Room in the basement of the Jefferson Physical Laboratory. Sabine developed a unique test setup and checked it for accuracy. He studied sound transmission through various layers of felt, interspersed with sheets of roofing paper. He also measured gypsum block walls, single and double, with absorbing material between the two layers.

J. Book 10

This book contains eleven pages of data and six separate (unbound) graphs on sound transmission loss. The structures tested are double panes of 0.25-in. plate glass, separated different distances apart, 1.5, 3.5, 6, and 12 in. Data are also recorded on the transmission loss through some porous materials.

K. Book 11

This book contains transmission loss data on felt, wood sheathing, iron, and iron and felt. At the end of the book there is a long list of people and addresses, some American, some European. The list appears to include the names of people to whom he may have contemplated sending his 1915 papers.

L. Book 12

The final book extends from May 15 to June 30, 1915, and from Fall 1918 until after Sabine's death. It contains extensive data on single and double panes of 0.25-in. plate glass at a number of spacings from 1.5 to 28 in. Sabine tested double panes at 1.5 and 28 in. with felt in the space between and single and double panes of 0.25 and 0.0625-in. glass. Various doors were tested. Beaverboard was tested in both single and double layers and with either granulated cork, sawdust, or magnesium particles in the space between. About a month before his death Sabine, with the aid of his assistant John Connors, calibrated a set of organ pipes, C_1 to C_7, making over 100 observations on each pipe on each of three nights. The project was called "Standardization of the Riverbank Organ Pipes, C_1 through C_7."

The final entry in Book 12 is a "Standardization of the Austin Pipes," which appears in the handwriting of John Connors with the explanation, "The observations were made by John Connors and Professor Sabine between the dates of December 13, 1918 and January 8, 1919 in the large lecture room of Jefferson Physical Laboratory with the settees and lecture desk in place. Original data are in Notebook *C*, pages 1, 2, and 3. Calculations were made April 10." Some additional notes were added by Connors on April 15 and August 1, 1919.

Wallace Clement Sabine died on January 10, 1919, at the age of 51.

II. THE DISCOVERY AND BOSTON SYMPHONY HALL

Prior to beginning the 12 notebooks, Sabine had already published one paper titled "Architectural Acoustics."[1] It was presented at the Annual Convention of the American Institute of Architects, November 2, 1898, and was published immediately. That paper recounts Sabine's investigations and his recommendations for improving the acoustics of the lecture room of the old Fogg Art Museum at Harvard (later renamed Hunt Hall and demolished in 1973).

Since this first paper was not included in Lyman's "W. C. Sabine, Collected Papers on Acoustics,"[3] I review it here because it summarizes his knowledge of acoustics just prior to his becoming the acoustical consultant to Boston Symphony Hall.

Sabine began the 1898 paper by stating that there are three important aspects of acoustics, namely, *loudness, interference*, and *distinctness*. He had found that optical instruments that measure sound pressure, such as a dancing flame, were of no help in studying acoustics because of the large amplitude variations from one place in a room to another.

Sabine had learned that the ear, listening to sound decay after a source is turned off, could judge accurately its duration, averaging out the fluctuations. He had found that judgments of different observers were closely alike and were repeatable in the dozen rooms he had studied. He presented a graph of data taken in the Fogg Lecture Hall which showed that the duration of the sound decay (known today as reverberation time) decreased smoothly with the addition of lengths of seat cushions taken from nearby Sanders Theatre.

Sabine observed that people and seats screen each other when close together, so that one person absorbs more sound alone than in an audience. He ascertained the relative absorbing power at 512 Hz of seat cushions, rugs, draperies, hair felt of four thicknesses, as well as an audience. He noted that different uses of a hall, for example, for speech as opposed to piano or chamber music, require different reverberation times. He also observed that the ability of an architectural irregularity to scatter sound reflected from it is greatest when the dimension of the irregularity exceeds a wavelength.

Finally, Sabine showed in this paper a sectional drawing of the Fogg Lecture Hall, together with his recommendations for remedying its poor acoustics. He described the placement of hair felt blankets, 0.75 and 1.5 in. in thickness, on 21 surfaces of the room, and the covering of the platform with a thick carpet. He stated at the conclusion of his paper, "The result was pronounced entirely satisfactory."

No indication of the "Sabine reverberation equation" appears in this paper although there is ample evidence[4] that he had discovered it four days before addressing the AIA in Washington, D.C. on November 2.

In mid-October 1898, President Charles W. Eliot of Harvard approached Sabine to say that he had spoken about his work on the Fogg Lecture Hall to Major Henry Lee Higginson, the master spirit and a principal donor for the new Symphony Hall to be constructed in Boston at the turn of the century. Eliot said that he had suggested that Higginson place responsibility for the acoustics in Sabine's hands. Sabine expressed hesitation but replied that he was interested and would give the matter consideration. Sabine devoted the next fortnight to a hectic review of the data he had taken during the preceding nearly three years.

On Saturday night, October 29, the answer came to him. His mother wrote in her diary,[4] "his face lighted with gratified satisfaction," as he announced quietly, "I have found it at last." His equation marked the beginning of the science of room acoustics and remains a cornerstone of calculation today. In brief, he found that the reverberation time in a room can be expressed by the formula

$$T=\frac{K}{a+a_1}, \qquad (1)$$

where K is a constant for a given room proportional to its volume; a is the initial sound absorption in the room before any sound absorbing materials are added; and a_1 is the added sound absorption (e.g., meters of seat cushions). In other words, a plot of T vs $(a+a_1)$ is a hyperbola.

Armed with a single formula, data at one frequency on the relative sound-absorbing properties of some materials and of an audience, and some general observations on room acoustics, Sabine hurried a letter off to President Eliot on 30 October 1898, promising that "It is only necessary to collect further data in order to predict the character of any room that may be planned, at least as respects reverberation." Eliot answered immediately, "I have written to Major Higginson, telling him the kind of help I think he could get from you towards the construction of a satisfactory Music Hall for Boston." Sabine's next year was spent frantically collecting the new data he thought necessary.

Sabine has documented clearly his part in the design of Boston Symphony Hall.[2] About 1888 Charles McKim of the architectural firm McKim, Mead, and White, prepared plans and a model of a hall along the lines of a classical Greek theater. But consultation by McKim and Higginson with a number of conductors exposed the design as an "untried experiment and because untried... of uncertain merit." And so it was abandoned. In 1898 the project was revived, and the building committee decided to follow the general proportions of the Leipzig Gewandhaus,[9] but enlarged to increase the seating capacity by about 70%.

At this stage, in about January 1899, Sabine entered the project. He performed calculations of reverberation time using information later published in Parts VI and VII of Ref. 2. He reported in Ref. 2 (Part VII) that, had the design based on an enlarged Leipzig Gewandhaus been built, it would have had double the volume of the original and, hence, an excessively long reverberation time—calculated at 3.02 sec with a full audience compared to 2.30 sec for the Gewandhaus.

Sabine convinced the architects that they should base their design on the Old (then existing) Boston Music Hall, with two balconies instead of the Gewandhaus's one. The old Music Hall was well liked in Boston, and the reverberation time calculated for it was only slightly longer than that of the Gewandhaus. The length of the main floor in the final plan for the new hall was very near that of both the old Music Hall and the Gewandhaus.

Sabine proposed that a stage house be added to one end of the new hall, with the side walls and ceiling spread to direct the sound more effectively into the main hall. He recommended eliminating balconies on either side of the performers on stage in order to enhance the loudness of the orchestra. With this arrangement the new hall could accommodate nearly 200 more seats than the old. Sabine also wrote: "The new hall is not as high as the old and is not so broad." Consequently, with respect to its loudness, "I do not think that the new hall will, on the whole, be at a disadvantage in comparison with the old [and as for] reverberation or residual sound, the two halls will be very nearly the same... ."

Although Sabine makes no mention of it, the ornate interior of Boston Symphony Hall with a coffered ceiling, sidewall niches, and provision for statues, contributes significantly to its good acoustics. Whether Sabine or the architects pressed for these details is unknown, although it could have been the architects because of their desire to copy the features of the ornate Leipzig Gewandhaus.

One current myth should be laid to rest. The statues in Symphony Hall were not added as a later correction to bad acoustics. Their existence was planned from the beginning, and they were commissioned and installed, one at a time, over a period of years as donors were found.

Sabine was also concerned with the noise of the ventilating system. He wrote[3]: "Transmission of disturbing noises through ventilation ducts... is practically a legitimate and necessary part of the subject. ... [Ventilation] is best secured by a system... known as 'distributed floor outlets.' It has the additional merit of being, perhaps, the most efficient system of ventilation."

III. THE MYSTERY OF 1900–1904

The principal mystery surrounding Sabine is why there are no entries in the notebooks between April 1900 and the summer of 1904, a period during which he might be expected to have made measurements in the completed Boston Symphony Hall (see Table I). There are several possible reasons for this hiatus, no one of which is certain. Possibly they were all involved.

A. Hypothesis No. 1

[The discussion which follows is based on Orcutt's biography (Ref. 4), pp. 125–127, 150–159, Refs. 1 and 2, and the notebooks.]

This hypothesis assumes that Sabine did no acoustical work between 1900 and 1904. It could be that Sabine was in trouble with his colleagues in the Department of Physics and wanted to improve his relations with them after completing consultation on Symphony Hall.

Sabine had been appointed Assistant Professor of Physics in June 1895. Almost immediately, President Eliot, after consulting with the Chairman of the Department, turned to Sabine, then 27 years old, to correct the acoustics of the Fogg Art Museum Lecture Hall, which had been unusable from the day of its opening in early 1895. Sabine's colleagues in the Department of Physics looked upon his new assignment as a grim joke.[4]

Although all his colleagues tried to dissuade him, the adventure appealed to Sabine far more than any of his other current options. He courageously fortified himself against the pessimism of his associates. Of possible greater concern to those in his Department, he went beyond President Eliot's conception, which sought only to correct a defect in the Fogg Lecture Room. In fact, Sabine set himself the task of coaxing from science a logical answer to an age-old mystery of why in some rooms the acoustics are good, and in others they are bad.

For three years he isolated himself from his colleagues, except to teach the classes assigned to him. Most nights he worked until dawn. Because he had to catch up on sleep during the daytime, he may have given the impression that he was apathetic toward his academic work. Another irritant may have been his preempting of two laboratory assistants on his project, who together earned as much as he did. Since those assistants also had to sleep during the day, they were very likely of little help to other faculty members. One can also imagine the comment created by stories of Sabine and his assistants dragging hundreds of linear feet of seat cushions from Sanders Theater to Fogg Lecture Hall during the evening and returning them before the next day's classes.

But even more damaging, the intractable acoustical defects were to keep the Fogg Lecture Hall out of service for another three years. On 3 November 1897, President Eliot, impatient with Sabine's progress wrote, "Your explanation of November 3rd about your expenditures in making the investigation...is very far from satisfactory. You have made sufficient progress to be able to prescribe for the Fogg Lecture Room, and you are going to make that prescription. What the Corporation wants is to pay all the costs to date of that investigation. ... You will of course be at liberty to continue the investigation at your own discretion, and at your own charge."

Not one of the notebooks covers the experiments of 1895–1898; only the summary in Book 7, written in 1899, remains. But the published paper of November 1898[1] shows that by late in the spring of 1898, Sabine rendered his prescription for the Fogg Hall, and the recommended installation was completed by September. Unfortunately, Fogg Hall's acoustics fell short of Sabine's predictions. Sabine in two papers first described it as "entirely serviceable" (1898) but later reflected, "Although this room was in large measure remedied, it will not be taken as an example. ... It is not suitable for an opening illustration" (1910). Almost unusable, it was finally demolished in 1973 to make way for a new dormitory.

Then in 1898 just after Sabine discovered the reverberation equation, President Eliot asked him to consult on Symphony Hall in Boston. This commitment led to another two years of intensive night work. The staff in the Department had now endured five years of a young colleague who worked nights and slept through part of the days.

Of course, his excellent series of papers published in 1900[1] would have improved his standing in the Department. The Chairman wrote on 13 August 1900, "I hasten to congratulate you. ... You are now the authority. ..."

Sabine had been Assistant Professor since 1895. Surely in 1900 with his research triumph, he was ready for appointment to Associate Professor. But it appears that he needed first to demonstrate his willingness to be an effective Department member. He seized on a section of President Eliot's report of 1900 as a guide to his next step. Eliot wrote: "The neglect of the subject of Physics by the students of the College and the Graduate School still continues, and is one of the most curious phenomena in the University today. ... the increase in number of students in physics ... ought to be large and rapid."

Sabine persuaded Department Chairman Trowbridge to allow him to teach an undergraduate physical measurements course, "Physics C." In three years the attendance in the course jumped from 69 to 236. In his 1903 report to President Eliot, Trowbridge said: "The marked success of this elective is due to Professor Sabine, who has devoted himself to the perfection of apparatus and to the enlargement of laboratory accommodations." In the following year's report to the President, Trowbridge states: "Physics C now occupies three large laboratores .... The success of this elective is due to the constant effort of Professor Sabine to increase its instrumental appliances and to raise its intellectual level."

Except for a bonus of $500 following completion of the acoustic corrections for the Fogg Lecture Hall, Sabine's salary stayed constant at $2000 per academic year from 1895 to 1904. It was increased to $3000 in the 1904–05 academic year.

In 1905, Sabine's promotion came—a *double* advancement to full Professor, which his biographer says caused Sabine real embarrassment. President Eliot commented on this delayed promotion, which, according to the biographer, always mystified Sabine's family and friends, but Eliot offered no explanation: "Sabine served five years as Instructor in Physics and ten years as Assistant Professor at Harvard University before he reached the position of full Professor, in spite of the fact that he quickly proved himself an admirable teacher and a highly successful investigator." As a full Professor, his salary was raised to $4000 and it remained the same for the next 10 years.

Immediately after his promotion, Sabine again surprised his colleagues when, after many years of not having taken part in the meetings of the Faculty, he proposed early in 1906 a radical change in the organization of Applied Science at Harvard. This proposal suddenly elevated him to the post of Dean of the Graduate School of Applied Science, which he held for 9 years with an annual supplement to his professorial salary of $500. His biographer says that he took the position of Dean only after much persuasion by President Eliot because his first loves were research and teaching.

Thus, the first hypothesis—that Sabine deliberately turned away from acoustics after 1900 in order to mend his academic career—has considerable support.

B. Hypothesis No. 2

[The following discussion comes from Ref. 2, Parts IV, VI, and VII; Ref. 4, pp. 130, 144–148; Refs. 7, 9, and 10, and the Sabine notebooks.]

This hypothesis assumes that Sabine was not satisfied with the results of his acoustical activities and that for this reason he destroyed the data taken between the spring of 1900 and the summer of 1904.

By the end of 1900, Sabine was fatigued after five years of prodigious personal effort; his wife, several friends, and the President of Harvard expressed their concern to Sabine.[4] Moreover, he may have suffered a state of depression when the Fogg Lecture Hall proved not to be a complete success, the reviews of the Boston music critics on the sound of the new Symphony Hall were not unanimously enthusiastic, and his bold public predictions of the reverberation time of Symphony Hall were not borne out in post-construction reverberation measurements.

Certainly, any experimental scientist of Sabine's caliber could be expected to test the results of applying his reverberation theory to a practical situation like the new Symphony Hall. But not a shred of evidence in the 12 notebooks, his published papers, or his biography suggests that he took any interest whatsoever in Symphony Hall after its completion, except to attend, with his wife, the opening night's concert. Could his measurements have been contained in the hundreds of missing pages cut from the notebooks? Theodore Lyman had observed that Sabine's depression over his work in acoustics had caused him to burn considerable material. It may also be significant that he received no fee or bonus for his advice on Symphony Hall.

Reference to Table I shows that Sabine did not use his notebooks in the same sequence as they are now numbered. Because the first seven notebooks as numbered were purchased about the same time, as indicated by details of printing, he could have recorded his observations on Symphony Hall after it opened in any one or more of Books 2, 3, 5, or 6, and later cut out and destroyed those pages. Of course, the material that was destroyed was not necessarily acoustical data, but there is no hint of what else it might have been.

In an index I have prepared which cross references the material published in Sabine's papers with that in the 12 notebooks, all the technical data published in his papers are accounted for in the notebooks, with three exceptions.

1. Part I of Ref. 5, a brief report on five musicians who judged the acoustical quality of five rooms as different numbers of Sanders Theatre seat cushions were introduced to vary the reverberation time.

2. The bases for two graphs in Ref. 6 which give the reverberation times in St. Paul's Cathedral in Detroit and the effect of an air space behind a layer of felt on its sound-absorbing properties.

3. The basis for one graph in Ref. 7 on the sound absorption of three types of acoustical tile. This graph was presumably derived from data taken for the Johns-Manville Corporation in 1911, but no data taken for that Corporation appear in any of the notebooks.

Fortunately, there is no reason to believe that Sabine destroyed any of the data taken after 1914 on sound transmission through doors, windows, and walls, as was feared by Lyman in his introduction to the "Collected Papers."[3] The dates of the extensive experiments described in the books (see Table I) agree closely with the activities reported for this period by his biographer. There appears to be no period in which he could have taken appreciable additional data. Lyman, of course, did not know of the existence of the 12 notebooks, but believed that all of Sabine's notes were destroyed.

Sabine's behavior in similar circumstances convinces me that he would have wanted to show the usefulness of his acoustical theory and data in predicting the reverberation times of auditoriums. In June 1900,[2] he wrote, "In the present paper it is the purpose to show the application of the preceding analysis and data, taking as an example the design of the new Boston [Symphony] Hall now under construction." He then went on to calculate, from drawings and descriptions, the reverberation times of the *Leipzig Gewandhaus* (destroyed in World War II), the old *Boston Music Hall*, and the projected *Boston Symphony Hall*. At 512 Hz he calculated the reverberation times, with full audiences, as 2.30, 2.44, and 2.31 sec, respectively. He continued, "As this is the first example of such calculation all the elements will be shown." Indeed, he listed in three tables the volumes of the three halls, the areas and sound absorptions at 512 Hz of all the surfaces, and the number of persons in the audience and the orchestra, as well as their total sound absorption. The data in the three tables are for full occupancy of the halls, "no account being taken of standing room."

In another table in Part VI entitled "Absorbing Power of Settees, Chairs and Cushions," Sabine gives measurements for chairs upholstered in "hair and leather," like those in Symphony Hall, an absorption per chair of 0.3 (in physical units of square meters). Using 2579 people and 80 musicians, as Sabine did for the occupancy of Symphony Hall, gives a total absorption of about 800 units for the empty seating area, as opposed to 1173 units for the fully occupied seating areas. Other surfaces in the room, he wrote, contribute 119

TABLE II. Comparison of predicted and measured reverberation times in the Boston Symphony Hall.

Reverberation times	Predicted	Measured
Unoccupied hall	3.26 sec[a]	2.7 sec[c]
Fully occupied hall	2.31 sec[b]	1.8 sec[c]

[a]From Equation (2).
[b]Wallace C. Sabine, *Collected Papers on Acoustics*, revised ed. (Dover, New York, 1964). p. 67.
[c]L. L. Beranek, *Music, Acoustics, and Architecture* (Wiley, New York, 1962), pp. 562, 565.

units of sound absorption. In terms of Eq. (1),

$$T(\text{unoccupied Symphony Hall}) = \frac{0.164\times 18\,300}{919} = 3.26 \text{ sec}, \quad (2)$$

where, 0.164 is a constant inversely proportional to the speed of sound (sec/m) and 18 300 m^3 is the volume of the hall. Thus although Sabine did not publish this number, it is easily calculated for comparison with data he could have taken in the unoccupied Symphony Hall.

Sabine's biographer wrote, "Ever since Mr. Sabine laid his formulas of proportions and materials before the architects of the Hall, he has maintained that there was as little question about the desired outcome as there was in the minds of the architects about the appearance of the structure." In another place the biographer wrote, "Then came the announcement that McKim, Mead & White ... had placed the responsibility for the acoustics entirely in Sabine's hands.... When the youthful expert supplemented this announcement by guaranteeing that the new hall should be acoustically perfect, he issued a challenge to the skepticism of architects throughout the world." Also, the biographer believed that Sabine and his family looked on Symphony Hall as a proof of the validity of his formula: "Music was an unknown realm to [his mother], for her Quaker family looked upon such indulgence of the senses as worldly and reprehensible. She may have preferred, therefore, to consider this new Symphony Hall as a temple erected to demonstrate the power of Science as expressed in her son's achievement, rather than as a monument to sinful personal gratification."

Thus the background of home, the extreme care used in cross checking all his research data, whose collection had required a near-superhuman effort over a period of five years, and Sabine's pride and confidence in his formulas and data could have laid the basis for deep disappointment if the measured results failed to confirm the predictions he had published in his paper of 1900.[2]

Orcutt apparently thought Sabine had made measurements in the completed hall because he wrote, "These calculations [of reverberation time at 512 Hertz] were completely verified in the final tests." Orcutt could only have got this information from Sabine's widow who had commissioned the biography and had approved every line in it.

If indeed Sabine did measure the reverberation times shortly before or after Symphony Hall opened, we can imagine his dismay upon learning, from data taken with his usual care, that the measured reverberation times were at least 20% shorter than his predictions, as we see in Table II.

One can understand Sabine's reluctance to answer more precisely a letter from the music editor of the *New York Times*, written a fortnight before the formal opening of Symphony Hall. Henry E. Krehbiel asked Sabine whether he had applied acoustical tests to the Hall since its completion or if he intended to do so at the opening concert. Krehbiel speculated that Sabine had predicted reverberation times with the hall empty, which he had verified, as well as with the hall filled, and that the opening concert would provide the opportunity to make the latter comparison.

I hasten to make clear that as far as Sabine's use of the predictions in designing the volume and shape of the new hall is concerned, the discrepancy in prediction made little difference. His primary concern was to compare his calculations for the new Symphony Hall with those for the then-existing Boston Music Hall, and because their volumes were nearly equal, his calculations for the two halls were about equally high.

Sabine replied to Krehbiel that the only real test of his work must come with the actual use of the hall for the exact purpose of its erection.

The principal reason that Sabine's predictions of reverberation time were inaccurate was that he made a bad choice between two ways of using the data on audience (or chair) absorption that he had taken in the Jefferson Physical Laboratory. It is now known (see Ref. 9) that audience (or chair) absorption is best calculated on the basis of the sound absorption per square meter of floor space occupied by the audience (or chairs). Although Sabine reported his data both ways, he chose to calculate audience (or chair) sound absorption on a "per person" basis.

In his published section on "The Absorbing Power of an Audience,"[2] Sabine gave his measured "audience absorption per square meter" as 0.96, which, when compared to his "audience absorption per person" of 0.44 (units of m^2) indicates an area of 0.46 m^2 (4.9 ft^2) per person. He referred to the audience of the new hall as being "seated with moderate compactness." Because of its upholstered arm chairs, the floor area per chair in Symphony Hall is about 0.53 m^2, or about 15% greater, which accounts for a large part of the 20% difference between the measured reverberation times and Sabine's calculations.[3]

In view of this history, it is not impossible that Sabine destroyed his data on Symphony Hall because he was distressed by his faulty predictions.

C. Hypothesis No. 3

Perhaps the most prosaic hypothesis would hold that Sabine cut the pages from seven of the twelve notebooks simply because the information in them had no relation to his published works or to the completed Symphony Hall and he wanted to save only material of historical value. Or possibly the notebooks were first used for some other purpose, and the irrelevant material was excised before he began recording acoustical data in them. Because there were other periods for which no acoustical data are found, we should look to them to see what clues they may offer.

Table I shows four periods in which Sabine apparently recorded no acoustical data. For the first gap of 1900–1904 a detailed study of the Orcutt biography reveals no reasons for the gap other than those covered in hypotheses 1 and 2.

The second gap of 1906–1908 corresponded to Sabine's first two years as Dean of the Graduate School of Applied Sciences. He also served from January 1906 to June 1908 on the Harvard Committee on Admissions. The Chairman of that Committee reported that Sabine was working so hard that one night he fainted in a restaurant in Harvard Square and a doctor was summoned. Also, Sabine wrote two technical papers which were published in 1906 and 1907. It may well be that he was too pressed by other academic activities to indulge in all-night tests in the Constant Temperature Laboratory.

The gap of 1909–1914 was a period of frenzied activity for Sabine. He was still the Dean of a growing school. His acoustic work with architects rose to a high level of activity (see the summary of Book 8 given earlier). In the courts he fought off an attempt by a conniving person to patent his techniques for using hair felt blankets in rooms as a control of reverberant sound. He was advisor to the Johns-Manville Corporation on the development of a nonflammable replacement for hair felt (later trademarked Akoustolith) and to R. Gustavino on the development of a porous ceramic building block that would obviate adding unsightly acoustical materials to a building surface. In early 1913 he developed the Schlieren-photograph method for studying sound reflections in models of theaters. Furthermore, he wrote seven technical papers, two of which were published in 1910; one each in 1912, 1913, and 1914; and two more in 1915. In a letter written in the summer of 1911 he stated, "I am keeping too many balls in the air. . . . Ich bin sehr müde [I am very tired]." Three times that summer Sabine fainted, the terrific strain culminating in a physical and nervous breakdown. He suffered a slight cerebral hemorrhage, and his right hand and leg were "slightly paralyzed." His biographer goes on to say, "From that time on he was never a well man."

The third gap of July 1915 to fall 1918 shows a similar frenetic activity. In 1915 he was appointed "Hollis Professor of Mathematics and Natural Philosophy" at $5500 per year, only $500 less than the salary of Harvard's President Lowell. He was completely absorbed with the dismal outlook for World War I and in June 1916, after receiving a leave of absence for the year with pay, he sailed to France and then traveled to Switzerland where he served the allied war effort by preparing a planning report for the International Tuberculosis Commission. In September, his colleagues in Switzerland and France thought he was suffering a collapse from overwork. In November, he narrowly escaped death when a raging abscess in his kidney broke and drained itself. From that illness he recovered rapidly and was able to present a long-promised series of acoustical lectures at the Sorbonne from late February to mid-May 1917.

In May and again in August 1917, he visited the battlefront on scientific missions, and after his return to the U.S.A. in September he spent four days of each week in Washington, D.C., advising on aircraft design and production until the war ended in November 1918. During that whole period he met his classes on Tuesdays through Thursdays.

During his last months, his mind was slipping. He frequently rose from the table, believing he had eaten, when actually he had not yet been served. He was constantly losing suitcases on his trips to Washington because he could not recall where he left them. He was in great pain. He was moody. Despite these troubles he met his classes and worked with his assistant John Connors, doing the work recorded in Book 12.

On January 7, 1919, he underwent an operation to remove his malignant kidney. His death followed three days later.

Sabine's combination of crowded days, confining responsibilities, and separation from his laboratory make it unlikely that he could have performed acoustical experiments during any of the gaps except the one from 1900 to 1904. Thus, the fact that no data survive from the 1900–1904 period sustains the mystery and justifies the detailed examination that has been given in hypotheses 1 and 2.

V. SABINE AS FRIEND AND COLLEAGUE

As professor, friend, husband, and father, Sabine was highly regarded by all his associates. His biography of 1933 is filled with praise from colleagues and friends. His biographer joined together in a fitting tribute the exact expressions taken from more than 20 friends who were closest to him:

> "In person, Sabine was a tall man, of slight and wiry build, with erect carriage. His face was extraordinarily attractive, declaring a gentle but firm character, which included highmindedness; a refusal even to be conquered by Science or Man; quick insight; perfect mental and moral directness; impregnable loyalty to truth, honor, and duty; wonderful singleness and tenacity of purpose; intellectual honesty; unusual consideration for others; highly developed consciousness; far-seeing vision; inherited idealism; and exaggerated generosity.
>
> "The singular elegance of his person was the expression of a rare elegance of mind; he was always calm and completely master of himself; yet gently modest, and self-deprecating, as if unaware of the positive importance of his work. By instinct, he was reserved and silent, yet a great master of con-

versation—too quiet to be brilliant, but implicitly witty; never controversial but startlingly intelligent and completely sympathetic; basing his comments on a store of accurate knowledge on all subjects, and showing a breadth of view and a catholicity of interest—with a soft voice behind which was a force that carried conviction."

Professor Emeritus Edwin C. Kemble is the only living member of the Harvard Physics Department who knew Sabine. He wrote to me on January 31, 1976, "Sabine was personally responsible for my coming to Harvard for graduate work. My undergraduate patron, Dayton C. Miller, who was also an acoustics man, wrote to Sabine and Harvard offered me a fellowship which Sabine paid for out of his personal pocket. I took Sabine's Optics the first year and liked him exceedingly. He had me at his Marlborough St. home for dinner and I remember once lunching with him to talk over a personal problem that was bothering me. But in the spring of 1917 he was off to war ... two years later he was gone."

Paul E. Sabine, a distant relative of Wallace and a Physics doctorate from Harvard, became the first Director of the Wallace Clement Sabine Laboratory of Acoustics (later renamed the Riverbank Laboratories), in Geneva, Illinois. That laboratory was designed in 1917 and 1918 by Wallace Sabine. He apparently intended to carry on his acoustics research there after the war. Paul wrote after Wallace's death, "To the scientist, Sabine's work appeals as being constructive to the highest degree. Definiteness of purpose, directness of attack, simplicity of method, and thoroughness and complete reliability of results distinguish it throughout. To the architect, it appeals strongly, because his results were always presented in a form immediately applicable to concrete and very troublesome problems."

The obituary "minute" prepared by his colleagues for presentation to the Harvard Faculty contains a fitting conclusion, "He succeeded by reason of a combination of qualities among which were unending patience and untiring energy."

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[1]W. C. Sabine, "Architectural Acoustics," Am. Arch. Building News 62, 71–73 (Nov. 1898). This paper is not contained in Ref. 3.

[2]W. C. Sabine, "Architectural Acoustics," published in seven parts in 1900: "I. Introduction, April 7; II. Reverberation: Absorbing Power of Wall-Surfaces, April 21; III. Reverberation: Approximate Solution, May 5; IV. Reverberation: Rate of Decay of Residual Sound, May 12; V. Reverberation: Exact Solution, May 26; VI. Reverberation: The Absorbing Power of an Audience, and Other Data, June 9; and VII. Reverberation: Calculation in Advance of Construction, June 16," Am. Arch. Building News 68 (1900). These papers are reproduced in Ref. 3.

[3]Wallace Clement Sabine, *Collected Papers on Acoustics*, prepared by Theodore Lyman (Harvard University, Cambridge, MA, 1922); available from Dover Publications, Inc., New York, NY, with a new introduction by F. V. Hunt (1964). Ten papers are included, published in 1900, 1906, 1907, 1910 (2), 1912, 1913, 1914, and 1915 (2). An unpublished manuscript concludes the volume.

[4]William Dana Orcutt, *Wallace Clement Sabine, A Biography* (Plimpton, Norwood, MA, 1933). Out of print. A few remaining copies are available from Leo Beranek at the cost of binding.

[5]W. C. Sabine, "Architectural Acoustics: I. The Accuracy of Musical Taste in Regard to Architectural Acoustics (Piano Music): and II. Variation in Reverberation with Variation in Pitch," Proc. Am. Acad. Arts Sci. (2) (June 1906). These papers are contained in Ref. 3.

[6]W. C. Sabine, "Architectural Acoustics, Correction of Acoustical Difficulties," Arch. Q. Harvard Univ. (March 1912). This paper is contained in Ref. 3.

[7]W. C. Sabine, "Building Material and Musical Pitch," The Brickbuilders 23 (January 1914). This paper is contained in Ref. 3.

[8]W. C. Sabine, "The Insulation of Sound," The Brickbuilders 24, (2) (February 1915).

[9]L. L. Beranek, *Music, Acoustics and Architecture* (Wiley, New York, 1962).

[10]L. L. Beranek, "Audience Absorption in Large Halls. II," J. Acoust. Soc. Am. 45, 13–19 (1969). A preliminary version of this paper was published in J. Acoust. Soc. Am. 32, 661–670 (1960).