Hollow Stones, Extruded Shells:
An Example of Evolutionary Process in the Servant/Served Dialogues of Louis Kahn

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"In the very fabric of making it must already be the servants that serve the very things I've talked about-its timbre, its light, and its temperature control; the fabric of construction must already be the container of these servants."[1]

Louis I. Kahn, "New Frontiers in Architecture," 1959

INTRODUCTION

Louis Kahn displayed a boundless inventiveness in his approach to typical building programs, once telling an associate on the Salk Institute project to "design as if there has never been a lab built before."[2] Even when a program was repeated in his *oeuvre*, each iteration was seen as a fresh start, resulting in art galleries as diverse as his two projects at Yale, for example, or proposals for sacred space as different as the First Unitarian Church of Rochester, NY and the Mikveh Synagogue project. Yet underlying this continual re-invention lay a decidedly empirical process, and an interest in continual refinement of certain architectural and engineering concepts that arose again and again throughout his career. Kahn was never above recycling an earlier design for a system, component, or detail, seeing in each project an opportunity to learn from past experience and to improve on what had gone before.

Kahn's designs for the Salk Institute for Biological Studies in La Jolla, CA, and the Kimbell Art Museum in Fort Worth, TX, seem at first to have little in common. One is a working laboratory on an oceanside cliff, with starkly expressed concrete shear walls and a section arising from onerous requirements for supply and exhaust air provision. The other is a relatively small museum in a more or less suburban setting whose section was derived from the combined requirements of light, space, and curatorial flexibility. Yet a closer look reveals that the two projects share several solutions to similar design problems. The Kimbell, begun while the Salk was in its closing stages, also benefited from the earlier project's sense of experimentation in the development of a range of details – notably its stair handrails and glass curtain walls.

With this in mind, a detailed examination of the two projects reveals a provocative set of parallels in their approaches to structure and services integration – what Kahn referred to as 'hollow stones.'[3] While the Kimbell took a different attitude toward the more refined spatial requirements of its program, its relationship to an early, folded plate scheme for the Salk is demonstrably one of direct evolution: its integration of structure, mechanical systems, space and daylight is an obvious step from a source in common with the Salk's final sectional solution. What this says about the two structures, and about Kahn's process, suggests a reconsideration of Kahn as an experimentalist in the operational, structural and constructional grammars of building. Similar details, components, and systems in the Kimbell and the Salk reveal that underlying these two radically different buildings was a common search for holistic solutions to problems of assembly, operation, and expression, whose ultimate test lay in the realm of human experience.

BACKGROUND – THE EVOLUTION OF THE SERVANT/SERVED RELATIONSHIP IN KAHN'S WORK

As early as his 1949 essay "Monumentality," Kahn recognized the potential for an integrated approach to structure and services, lamenting the experiential poverty of standard, 'handbook' engineering and suggesting instead that steel could be developed based on new structural principles, transcending the post and lintel approach inherited from the Greeks and, in his view, still present in the configuration of the typical I-beam.[4] In the two decades between this initial theoretical exploration of building technology's cultural potential, Kahn returned several times to the notion of 'hollow stones,' that is, physical hybrids of structural and mechanical performance, or structural solutions that would contain a building's circulatory needs.[5] This approach would define much of his work during his final decades, as he took on a series of complex building projects that required just such a careful deployment of resources and space – whether for economical, sectional, or functional reasons.

The combination of structure and services into a single, integrated section first manifested itself in Kahn's large scale work in the Yale Art Gallery of 1951-53, where a tetrahedral grid was manipulated to allow duct runs within its triangular section. Experimentation with Vierendeel beams, using strategically placed voids in structural members to allow through passage for services, was again explored in the 1954-57 American Federation of Labor Medical Services Building in Philadelphia. Here, steel beams were cut and re-welded to form hexagonal openings, expressed in the lobby but used in interstitial spaces to allow pipes and ducts unfettered access to the floors below. Around this time, in 1954, Kahn articulated his developing philosophy of expressed services integration during a talk at the North Carolina State School of Design:

> *"We should try more to devise structures which can harbor the mechanical needs of rooms and spaces and require no covering."*[6]

This sensibility is evident as early as Kahn's plans for the Mill Creek Housing project of 1952-3, in which free planning of the apartments was possible due primarily to the incarceration of various service elements – stairs, ductwork, and elevators – within two u-shaped shear walls at each floor plate's center. Simultaneous experimentation in the segregation or corralling of services in plan has been most widely noted in the Trenton Bathhouse of 1955-57, in which toilet rooms occur in the 'hollow columns' that occupy the intersections of the overall scheme's tartan grid. These prototypical 'servant spaces' themselves had precedents at the Yale gallery, though, where the gallery's stairs and lifts occured within a central zone, held back from the columns supporting the grid floors in their own structural cage of shear walls.

Indeed, most interpretations of Kahn's "servant/served" dichotomy rely on plans or volumetric distinctions to show how space was reserved for ductwork, toilets, transport and servicing, rather than the more subtle parsing of his interstitial sections to show how this was achieved on a finer scale. Richards Laboratory of 1957-60 is traditionally seen as the paradigmatic example of this, in that tall vertical shafts containing these functions were placed entirely outboard of the otherwise square laboratory modules. While the result of this at Richards is a flexibility in lab planning – with no fixed shafts in the work spaces, equipment and personnel could be moved around at will – an equally important development here was the inclusion of precast, post-tensioned Vierendeel floor beams. These elements, engineered by August Komendant, allowed the structure to be rapidly assembled, tinkertoy fashion by crane.[7] More importantly, they permitted the main service trunking to branch out by weaving between the minimal verticals of the Vierendeel system, while the beams' lower chords could be exposed in the labs to provide a structural 'grain' to the spaces. There was thus no need for a dropped ceiling below the structure to accommodate the sectional space requirements of the ducts and pipes – both structure and services occupied the same interstitial dimension. While the external, vertical cores defined the architectural expression from the exterior, the effect of the floor beams on the internal spaces was somewhat more pervasive, allowing the ceiling plane to step up in the corners, where both structural and mechanical loads diminished. Likewise, in these spaces the elevational split of the lab modules into four quadrants by the central towers was replaced by the nine-square grid of the actual structure and its harbored floor level pipes and ducts.

The ceilings of Richards were thus designed to exploit fully the hollows in the structural section, and to allow access to the interstitial zone from any point in the labs. Dust that collected on these pipes proved to be a major problem, as many work areas required ideally hygenic conditions, however a deeper issue proved to be the servicing and changing out of the pipes and ducts above as lab groups moved in and out of the building. Access to the interstitial spaces of Richards was entirely dependent on the floor below, and any tinkering or replacement in the ceiling necessitated the movement of furniture, workbenches, etc. Labs could not be serviced 'online', and work had to cease while mechanics or technicians worked overhead.

HOLLOW STONES — THE SALK INSTITUTE

This issue of access was a determinant factor in Kahn's next iteration of the sectional servant space, at the Salk Institute. Here, while the original program was based on that of the Richards building – Salk having visited Philadelphia in 1959 and remarked on its similarity in size to his proposed Institute – the solution was formally distinct, yet related in important ways to the previous project.

In order to allow for rapidly changing laboratory groups, Salk demanded that the laboratory floors be infinitely flexible, permitting equipment, benches, and rooms to be installed or dismantled as needed. Working again with Komendant, along with mechanical engineer Fred Dubin and the Institute's laboratory planner, Earl Walls, Kahn developed two schemes to meet this demand. The first, consisting of two layers of folded plates with lab space in between, relied on the hollow shape of the spanning plates to carry piped services, while ductwork was suspended beneath the plates between two downstand beams carrying post-tensioning cables. Services were to drop through this lower zone, between the ducts, to meet the lab space in a series of plug-in panels. Drainage for each lab level was handled by sub-floor services, on the upper level by the hollow beams below, and on the lower level by an undercroft running the length of the lab blocks. With this arrangement, no space in the clear-span laboratories would have been more than 10′-0″ from a potential service point, and the effects of the folded plate would have lent a visible grain to the often chaotic lab spaces, including daylight from ceiling slots between the plates on the upper level.

This original scheme was rejected by Salk, ostensibly for its site planning issues, but also because the 10′-0″ module did not permit as fine a servicing grain as he envisioned. Likewise, problems with integrating the ducts into the relatively small downstand zone would have been significant. Faced with a suddenly tight design schedule, Kahn reverted to a version of the Richards section, a series of 9′-0″ Vierendeel trusses – this time spanning only one direction – with the addition of a perforated slab at the level of their lower chord to physically separate the combined structural/service zone from the clean lab spaces below. This slab included cast-in aluminum slots on a 5′-0″ linear grid to allow more flexible service provision to the lab spaces beneath, and had the added benefit of allowing maintenance and changeover in the newly created interstitial level without disturbing the occupants below. In "giving the pipes a floor of their own", Kahn solved a number of issues that had arisen at Richards, improving on the original solution in an iterative fashion. There is evidence to suggest that the Vierendeel here was Kahn's idea, and that Komendant's contribution was in designing the structural component of an integrated scheme whose overall arrangement had already been decided.[8] Sketches from Kahn's office show the Vierendeel section with major statical errors, indicating that the origin of this set of 'hollow stones' arose as Kahn's re-interpretation of the Richards floorplates. The hollows of the Salk's trusses were interwoven with a mechanical system designed by Dubin to permit maximum access and modularity from within the interstitial area itself, a scheme which has proven itself over the nearly 40-year lifespan of the labs.

Kahn lamented the 'loss' of the folded plate scheme, which he regarded as more architectural than the realized solution. Komendant, similarly, felt the Vierendeels were not structurally 'pure' nor expressive, as they required post-tensioning cables in their bottom members and were invisible to all but the Institute's maintenance workers. While the aluminum slots in the final scheme provided the required flexibility and offered some measure of order to the spaces below, for Kahn they were not as powerful an expression of the building's natural orders – structural, environmental, constructional – as the original scheme would have been. Whereas the building as built consists of hollow structural elements stacked atop one another – the interstitial floors – this is not the dominant effect of the lab spaces themselves. It is apparent from Kahn's commentary that this incomplete and rather scale-less appearance did not live up to the spatial promise of the original concept.[9] It would become clear that the fundamental recipe of the original, folded plate scheme maintained for Kahn its essential validity as a concept, and would act as a link to a more fully developed instance just as the Richards floor plates appear to have inspired the final Salk solution.

HOLLOW STONES – THE KIMBELL ART MUSEUM

The galleries of the Kimbell Art Museum, in Kahn's office from 1966 to its opening in 1972, were designed to meet the demands of Director Richard Brown that art be shown in rooms with diffused natural daylight, and that maximum flexibility in arranging exhibits be provided. Parallel to Kahn's well-documented experiments in urban form on the site, Kahn's office staff executed over one hundred sectional studies addressing these requirements as modular issues. These options all spanned large floor areas, introduced daylight, and carried services to each gallery, and they ranged from simple clerestory sections to vaulted sections with linear skylights cut through the apex, admitting light through baffles and reflectors, or by 'washing' daylight down the curved soffits. By Fall, 1967, Kahn's associate Marshall Meyers had begun preparing detailed sections of a vaulted scheme with a curved reflector in the center, a recognizable precursor to what was finally built. Nervous about the monumental spaces tendered by single-curved vaults, Richard Brown asked Kahn and Meyers to explore shallower shapes, and after seeing a cycloid vault in Fred Angerer's *Shell Structures* they began modifying the scheme to fit the lower curve.

Initially, the cycloid vault was sketched as a 20′-0″ span with a series of 'upset diaphragms' sticking up from its top surface to maintain the complex curve. Between these vaults, a 10′-0″ service zone was to be roofed by a flat slab, with ductwork carried by a downstand beam and metal tray. As Komendant worked through the statics of the vault, the diaphragms were replaced by a more robust arch at the end of each vault to hold the shape at the corners, and the flat slab was designed to act as a beam rotated on its side, taking the thrust forces of the vaults in their central regions.

Much has been written and indeed misunderstood about the structural behavior of the cycloids, even by Kahn himself.[10] The problem lies in part in thinking of the shapes as architectural 'vaults', that is, spanning the short dimension of the galleries. As described by contemporary authors, the complex behavior of 'long' cylindrical shells such as the Kimbell is essentially that of a beam, one that imparts a relatively small thrust in its sectional plane, but that incurs significant bending along its long axis.[11] This creates a tension region below the shell's neutral axis, and a compression zone above it. Internal stresses within the shell must be neutralized to avoid bending in the supporting columns at the shells' ends.[12] In standard industrial applications, this was handled by diaphragm walls at the ends of the shells, an architecturally unsatisfying solution. Kahn and Komendant considered other options, including an 'upset diaphragm' that would have formed an upstand girder above the shells before agreeing on a two-hinged arch that stiffens the shell and absorbs the internal bending. Likewise, the marginal beams neutralize these stresses along the lengths of the shells, and have the beneficial effect of providing extra steel reinforcing in the tension zone of the shell. Further tensile resistance was provided by extensive post-tensioning via steel cables draped through the depth of each cycloid.[13] While not strictly correct, it is useful to see the shell itself as the primary structural element, with the end arches, marginal beams, and post-tensioning essentially holding the shell's cycloid shape, preventing it from flattening at the edges or spreading in the center.

Perhaps the clearest illustration of the shells' true performance is given by Komedant in his book *Contemporary Concrete Structures*, and later published in his memoir, *18 Years with Architect Louis I. Kahn*. Here, Komendant drew the cycloids not as vaults, but rather as gull-wing shapes, with the marginal beams in the center of each unit and the skylights toward the edges. This is somewhat shocking to architecturally trained eyes, as it seems to ignore the spatial logic of the galleries and in particular the focused attention on the finely detailed aluminum reflectors. In effect, Komendant argued that the spatial grid of the Kimbell is actually staggered by one-half bay from the structural grid. This interpretation is confirmed by the somewhat odd termination of the structure's outermost cycloids. These alight upon concrete gutters whose bulky proportions admit that they serve a structural function as well, resisting the tendency of the shells to flatten out at their center by absorbing the relatively small bending moments in these regions, much as the end arches stiffen the shells by absorbing their internal bending forces. This slightly awkward detail – seemingly too large to be a simple gutter but too small to perform the familiar tasks of buttressing a perceived arch – is indicative of the complex, hybrid nature of the shells. Indeed, a structurally 'pure' solution to the portico vaults would have suggested leaving off the outermost half-vault, with the remaining shell terminating at its ridge line along which the internal stresses would have been nil.[14]

There are, of course, any number of arguments demonstrating that the complicated behavior of the shells is anything but a 'pure' expression of structural principles, as demonstrated by Peter McLeary, Guy Nordensen, and others.[15] Yet the additional functional requirements of the museum's mechanical system suggest that the cycloid shells seen holistically perform additional, non-structural tasks – integrating environmental, lighting, and curatorial requirements into a single, integrated whole. Kahn had originally conceived the galleries' mechanical systems as hanging below the marginal beam assembly, covered by a u-shaped metal plate. Komendant objected to this arrangement, as it would have obscured the lower edge of the shells, hiding a key element in the expression of the structural rhythm. Eventually, supply ductwork was tucked up into the section of the marginal beam itself, peeking below the downstand terminations of the shells to direct conditioned air into the gallery spaces. Intriguing in its simplicity, the exhaust strategy directed air out of the galleries at floor level, through a slot detail between the end walls and floor finishes that simply dumped air into the services undercroft. Thus the mechanical system operated on the staggered grid of the gull-wing structure, with supply ductwork in the revised module's center servicing galleries on both sides, in contrast to earlier schemes that showed a series of folded plates with a combined reflector/duct run through the center of each gallery.

The Kimbell vaults can thus be interpreted as a system balancing four needs – the experiential requirements of daylight and monumental space, accommodated in the rounded volumes of the 'vaults'; and the service requirements of air handling and structural span, accommodated in the deep section of the 'gullwing'. The museum's plan can thus be read as a version of the Salk's *section*, laid on its side so that its lab volumes transform themselves into galleries, while its interstitial floors become the service zones of the Kimbell. These servant zones, seen in the 'hollow stone' model of Kahn's earlier writing, carry not only the mechanical and structural systems of the building, they also carry mechanisms providing natural and artificial light. Furthermore, these zones house the majority of the building's vertical circulation – the service stairs, passenger elevators, and the main stairs connecting the two levels all occur within the plan depth of the vaults' marginal beams.[16] As if to emphasize this distinction, entries to the museum from the park – both from the west and from the pedestrian sidewalks along Camp Bowie Boulevard and West Lancaster Avenue – converge on the grid of the *vaults*. Access from the parking lot and from the lower entrance level is handled via stairways along the *gullwing* grid. In addition to the strong sense of cross-grain that the linear service zones add to the gallery spaces, there is thus a constant experiential distinction between servant and served spaces delineated by the contrast between the dramatic, light-washed shells and the lower zones between, with an 10′-0″ metal soffit, overhead.

If the clarity of the Salk's sectional division between service and functional spaces is best seen in the Kimbell's plan, the careful integration of the two can best be found in the sectional scheme of the Kimbell and, provocatively, the early folded plate sectional scheme of the Salk. In both cases, a concrete shell – in once case a folded plate, in the other a curved one – carry mechanical services in an underbelly designed for easy servicing and linear distribution. At their perimeters, both shells stop short of their module line to permit overhead daylight, and both use their structurally derived shapes to inform a powerful, modular space below – the 'bailiwick' of the Salk becomes the gallery of the Kimbell. While the latter project, being only one story, does not enclose the greater structural depth of the upper shell section, the original Salk scheme actually underused this structurally derived void, designating it for pipe spaces and access. Essentially, this and the distinction between curved and folded shapes are the only major differences in the conception of the two linear modules. This suggests that the 'mistake' of reading the Kimbell's structure as vaults would be analogous to reading the folded plate scheme of the Salk as a series of triangular spaces surrounded by pitched concrete ceiling slabs. Rather, this comparison suggests that the Kimbell be read as we imagine the earlier Salk scheme, as a series of linear, folded concrete spanning elements, carrying services beneath their centerline and lending definition, conditioned air, and daylight to the spaces on either side.

CONCLUSION — 'HOLLOW STONES' AND THE EMPIRICAL PROCESS

That such a similar system of structural and services integration should appear in two wildly divergent building types is indicative of Kahn's process, in which no solution was final and in which no piece of knowledge was discarded. The notable utility of the Vierendeel floor plates in the Richards project was a paradigmatic example of Kahn's interest in 'hollow stones,' or structure that could carry within its shape service spaces for the building to hand. These trusses were ultimately deployed in both the Salk section and, intriguingly, in the gallery floors of the Kimbell. Yet the Kimbell's added requirements of servicing and daylight led instead to a shell system that followed the logic of the earlier folded plate scheme for the Salk. From an art historical point of view, this is an untidy state of affairs, and it begs questions of authorship, influence, and collaboration — who was 'responsible' for the Kimbell shells? Komendant? Kahn? With or without Meyers?[17] In seeing the holistic nature of these elements, which simultaneously satisfied structural, constructional, and operational requirements, we glimpse the alternative interpretive strategy offered by a more technical assessment. Working with Komendant, Kahn had developed a folded plate scheme for the Salk that, while ultimately rejected, nevertheless provided a powerful integration of statics, services, and assembly. Faced with a new typology that offered similar challenges of daylighting, clear span, and flexible function, the design team revived the earlier, obviously much beloved folded plates — albeit with significant changes based on both the new requirements of the museum galleries and the accumulation of knowledge from the earlier scheme's failure.

An interview with Richard Brown shortly after the completion of the Kimbell is highly revealing of Kahn's approach and indicates the importance of iteration and empirical process. Faced with a shortlist of architects including Mies van der Rohe, Brown and his board were impressed by Kahn's approach more than his built work:

> *"I came to think Mies would impose his great creative contribution on this building on his terms and in his tradition – in spite of a totally new situation with a different climate and light. I felt Louis Kahn would approach this problem like Adam, for the first time, and indeed that's the way it turned out."*[18]

Kahn's approach turned out to be "all-embracing," letting "the specific situation posed by the creation of a building guide him and tell him what the structure, engineering, and esthetics ought to be."[19] This meant, therefore, that the specific solution of the Yale Gallery was never considered, and that the sectional solution began not from previous museum work, but from a search for the right solution to the complex problem dictated by overlapping and interdependent service and structure requirements. In rejecting an *a priori* solution, which Brown suspected Mies would have provided him, the process became a lengthy one, frustrating Komendant and driving Preston Geren, Kahn's associated architect in Fort Worth, close to legal action against Kahn on the project's behalf. Yet Brown recognized the value of this method:

> *"Only when the total project and the building itself tells you what it wants to become do you know you have the right answer...in the process of doing it [Kahn] finds a better way...eventually you arrive at better and simpler answers that accommodate everything that a modern building needs, in a much less expensive way, such as the mutually accommodating relationship between structural elements and mechanical elements."*[20]

Paradoxically, this process was driven by a series of preconceptions in Kahn's mind – not about how the museum should be shaped or organized, or what it should look like, but rather how a clear span, functionally flexible space demanding services and daylight could be accommodated along a linear module:

> *"That basic structural and space-creating idea did not emerge out of our discussions at all, that was already in Lou Kahn's mind and had been for a long time, I think. And when he was commissioned to do this particular job, he reached for that structural idea as ideal for it."*[21]

This was not, Brown insisted, an *a priori*, however:

> *"This was a selection out of a great many things that can be done with post-tensioned concrete...this is what every museum...has been looking for ever since museums came into existence: a floor uninterrupted by piers, columns, or windows, and perfect lighting, giving total freedom and flexibility to use the space and install art exactly the way you want."*[22]

It is useful to compare this statement with the original Salk program document, which led to the early, folded plate scheme.

Written by Kahn's office to summarize discussions with Salk, it stated:

> *"The Laboratories for the Biological explorations should be designed ready to give space and services to any of the natural and physical sciences. The enclosed spaces must be free of columns in order to make possible complete flexibility of physical and mechanical layout.... a loft space completely flexible in terms of partitions, benches, services, and the supply and control of air."*[23]

Here, then, is the fundamental similarity between the Kimbell and Salk – both provide clear span spaces for flexible programming, requiring daylight, servicing, and at least in the earlier Salk scheme a sense of order. Neither scheme is truly a 'loft' solution, although the final Salk section suggests this arrangement. Rather, both clients understood the need for space that offered a grain, a sense of monumentality to the activity below. That Kahn had defined this word, monumentality, in technical and objective ways in his seminal 1947 essay suggests that this interpretation of these two buildings – as empirically derived, integrated sections – connects them in ways not often noted. While the two buildings share details and materials – notably their curtain walls, concrete formwork and an approach to their handrail design – their most powerful similarity lies in the approach taken to the larger scale problems of providing defined yet unconfined spaces for highly serviced human activity. Seen this way, it seems obvious that a similar family of solutions were considered for both, and it seems appropriate that these solutions, while topologically similar, would nonetheless manifest themselves in ways that emphasized the distinctions in the two programs' required performance.

Given Kahn's partial understanding of the Kimbell roof shells' beam actions, it seems unlikely that the reappearance of the Salk's folded plate scheme in its cycloid guise was entirely conscious. Rather, the development of a conceptual, even philosophical approach to structure, services, and their potential relationship seems to have manifested in Kahn's sensibility an idea of appropriate order in considering these systems and, when deployed in a long span solution, an archetype combining their elements in ways that added a sense of grain to the functionally indifferent spaces below. This overarching view, of the building as a conscientiously ordered synergy of its parts, suggests an interpretation of Kahn's works that is slightly at odds with the standard literature, in that it opens up a realm of technically based architectural theory to complement the better-trod discussions of space, form, and composition.

In the midst of his often esoteric and occasionally self-contradictory spoken work, Kahn said in 1961 "a great building must begin with the unmeasurable, must go through measurable means when it is being designed an in the end must be unmeasurable. The design, the making of things, is a measurable act."[24] This measurable aspect of his work is all too often forgotten amidst the staggering spaces of his buildings and the unknowable phrasings of his writings. In this instance, the measurable realm provides a provocative link between two unmeasurable experiences, pointing out to us just how close the contingencies of design may be to the timelessness of form.

ILLUSTRATIONS

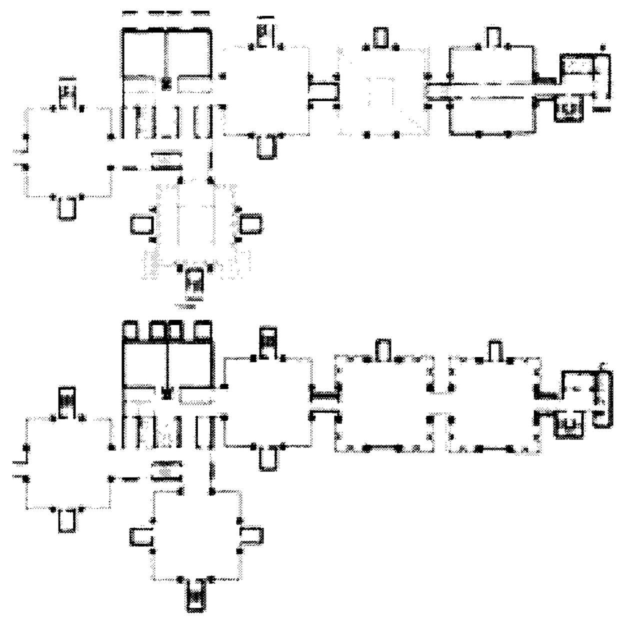

Fig. 1. Richards Medical Laboratories, Philadelphia, PA. Plan showing relationship of servant towers and served laboratories.

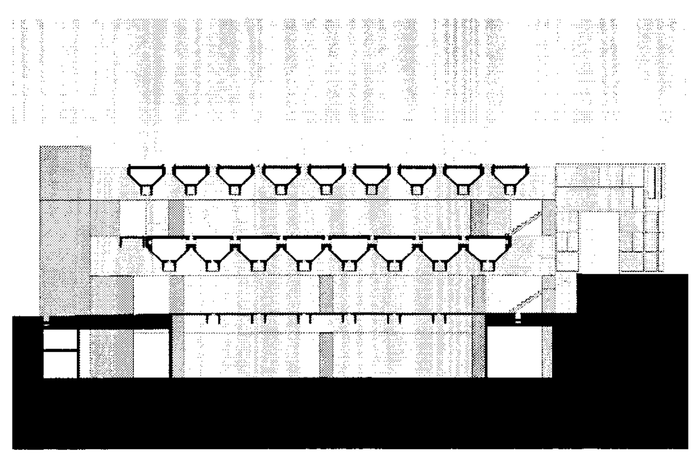

Fig. 2. Salk Institute for Biological Studies, La Jolla, CA. Section of early "folded plate" scheme showing precast beams combining structure and service voids. (diagram by the author).

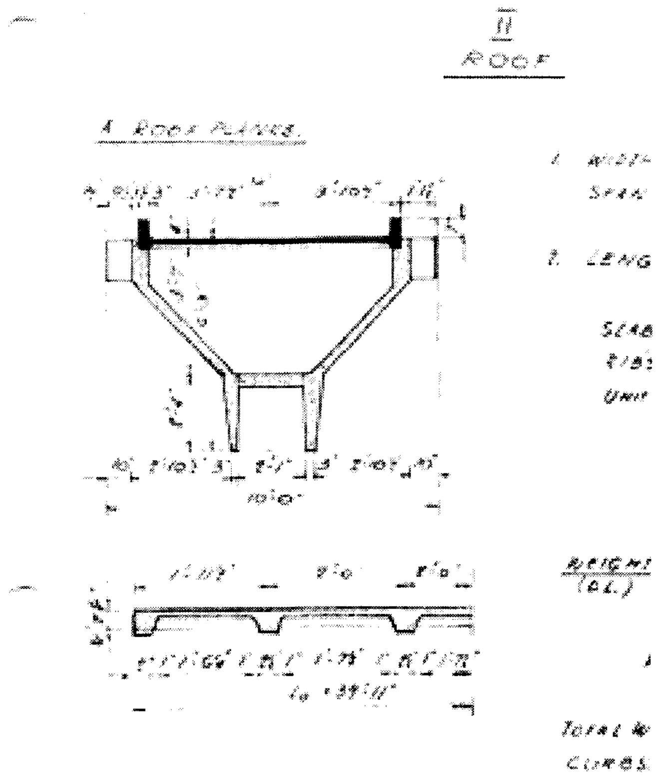

Fig. 3. Salk Institute for Biological Studies. La Jolla, CA. Structural sketch by August Komendant showing configuration of precast 'breathing beam'. (August Komendant Archives. University of Pennsylvania).

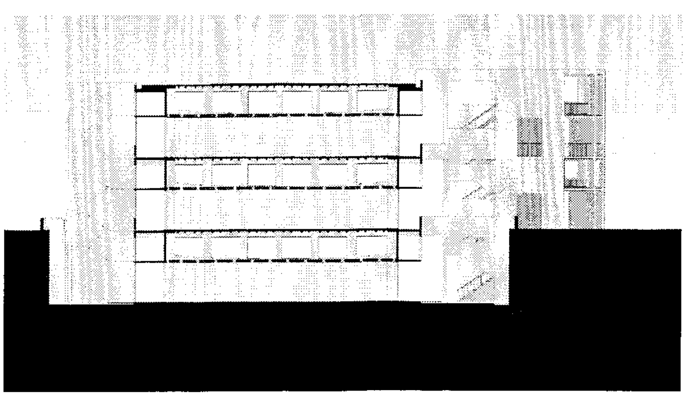

Fig. 4. Salk Institute for Biological Studies. La Jolla, CA. Diagram of scheme as built showing Vierendeel solution, integrating structure and services into interstitial floors.

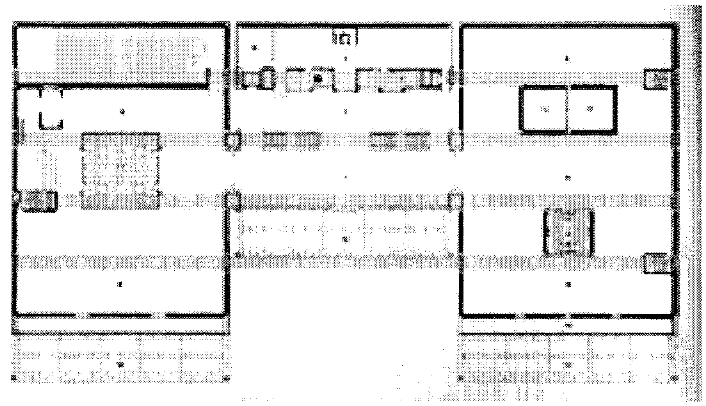

Fig. 5. Kimbell Art Museum. Fort Worth, TX. Plan of main gallery floor highlighting servant zones. Compare with section through Salk Institute, figure 4 above.

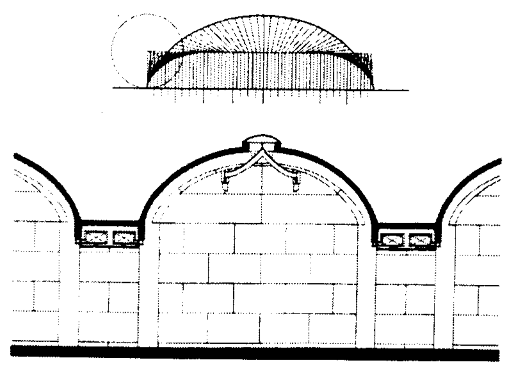

Fig. 6. Kimbell Art Museum, Fort Worth, TX. Detail of cycloid roof shell as traditionally illustrated.

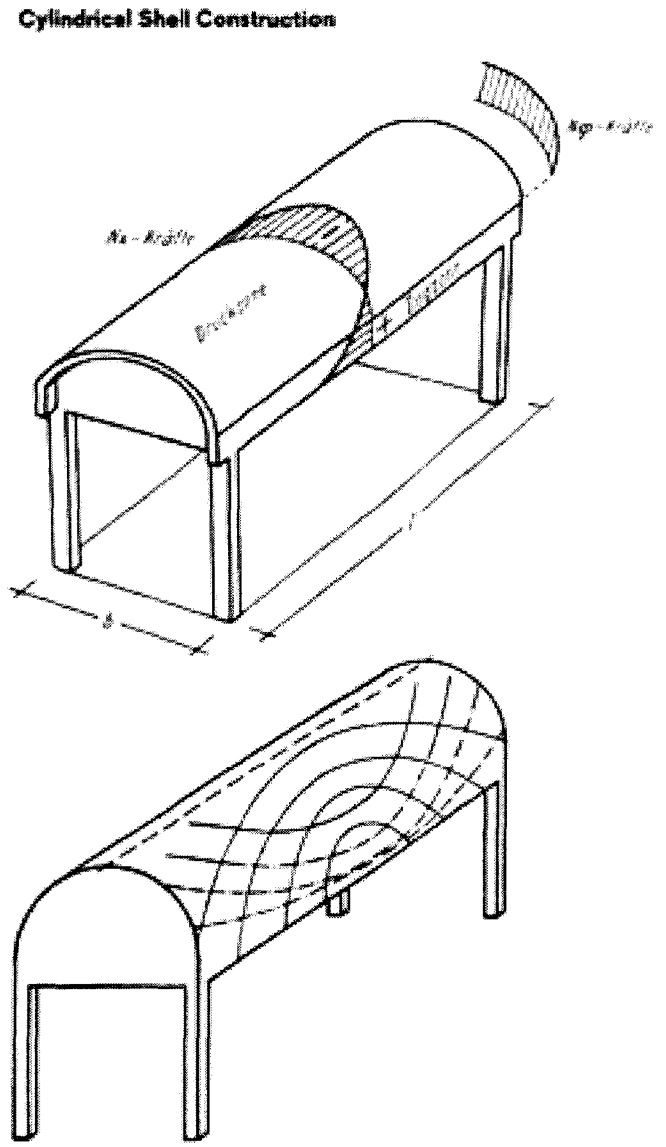

Fig. 7. Diagram of cylindrical shell structural actions showing (top) beam behavior through section and arch action at ends, and (bottom) isostatic lines of tension and compression through shell plane. From Jurgen Joedicke. Shell Structures.

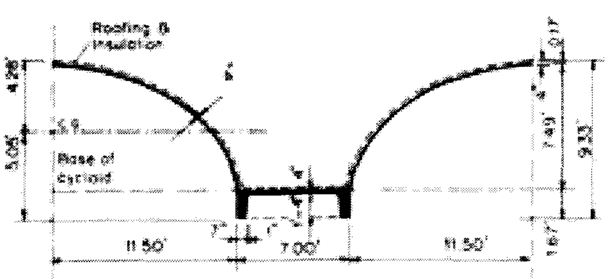

Fig. 8. Kimbell Art Museum, Fort Worth, TX. Cycloid roof shell as drawn by August Komendant. This drawing inverts the traditional architectural logic of the vaults, interpreting the shells as gathering elements centered on a service zone. From August Komendant, Contemporary Concrete Structures.

NOTES

[1] Alessandra. Latour.*Louis I. Kahn: Writings, Lectures, Interviews.* (New York: Rizzoli. 1991). 90.

[2] Conversation with Jack MacAllister, La Jolla, CA, June, 2001.

[3] LIK, "Space, Order, Architecture" (1957) in Alessandra Latour, *op. cit.* 80.

[4] LIK, "Monumentality" in Latour, Alessandra, *op. cit.*21.

[5] LIK, "Space, Order, Architecture" (1957) in Allesandra Latour, *op. cit.* 80.

[6] Louis Kahn, "How to Develop New Methods of Construction," in Alessandra Latour, *op. cit.* (New York: Rizzoli, 1991). 57.

[7] LIK: "One day I visited the site [of the Richards Laboratories] during the erection of the prefabricated frame of the building. The crane's 200-foot boom picked up 25-ton members and swung them into place like matchsticks moved by the hand. I resented the garishly painted crane, this monster which humiliated my building to be out of scale.... Now I am glad of this experience because it made me aware of the meaning of the crane in design, for it is merely the extension of the arm like a hammer. Now I began to think of members 100 tons in weight lifted by greater cranes..." in Latour, *op. cit.*, 119.

[8] Sketches in the Kahn Archives, reprinted in ... show a Vierendeel section that is quite obviously incorrect statically-suggesting that Kahn led the development of its initial conception. Likewise, Komendant was, at the time of the Vierendeel's appearance, engaged on the redesign of the folded plate scheme, eventually complaining that he had been out of the discussions that led to the final scheme. See Thomas Leslie, "Things in Their Best Order: Technical Aspects of the Salk Institute and Their Role in Its Design" *The Journal of Architecture*, Spring, 2003 (forthcoming).

[9] LIK: "Dr. Salk, when his belief in what must constitute the nature of a laboratory space was fully realized, could not turn back to something that was less than what we finally accepted, even though it meant drastic change. I felt the loss of the folded plate construction. My structural engineer was not for change. The mechanical engineer still believes that the folded plate could work. Yet study and new architectural potentialities finally gave rise to everyone's belief in the validity of the last choice." in Latour, *op. cit.I 207.*

[10] LIK: "The changing dimension of the slits at the ends of the vaults are caused by the fact that the end pieces are semicircular and the vaults become wider as they go down. The vaults need power at the top. It's contrary to what you would expect. It is light at the sides and heavier at the top. At first it was hard for us to get used to it, but this is Komendant's fearlessness." in Richard Saul Wurman, *What Will Be Has Always Been: The Words of Louis I. Kahn.* (New York: Access press/Rizzoli, 1986) 238.

[11] See in particular Jurgen Joedicke, *Shell Architecture*(New York: Rheinhold, 1963), Mario Salvadori, *Structure in Architecture: The Building of Buildings* (Englewood Cliffs, NJ: Prentice-Hall, 1963)) and most notably Fred Angerer's excellent *Surface Structures in Building: Structure and Form* (New York: Rheinhold, 1961). This last volume was consulted by Kahn associate Marshall D. Meyers, who credits its illustrations with providing the inspiration for the particular cycloid shape chosen. While the cycloid itself was unusual, numerous cylindrical vault structures statically similar to the Kimbell were built, largely in industrial contexts, throughout the 1950s and 1960s.

[12] At the Kimbell, this is ensured by Komendant's provision of a dowelled, neoprene connection between vault and column, creating a hinge condition. See August Komendant, *Contemporary Concrete Construction* (New York: McGraw-Hill, 1972) 507 (fig. 319).

[13] August Komendant, *My 18 Years with Architect Louis I. Kahn* (Englewood: Aloray Publishers, 1975).

[14] Joedicke, *op cit.* includes stress diagrams showing this.

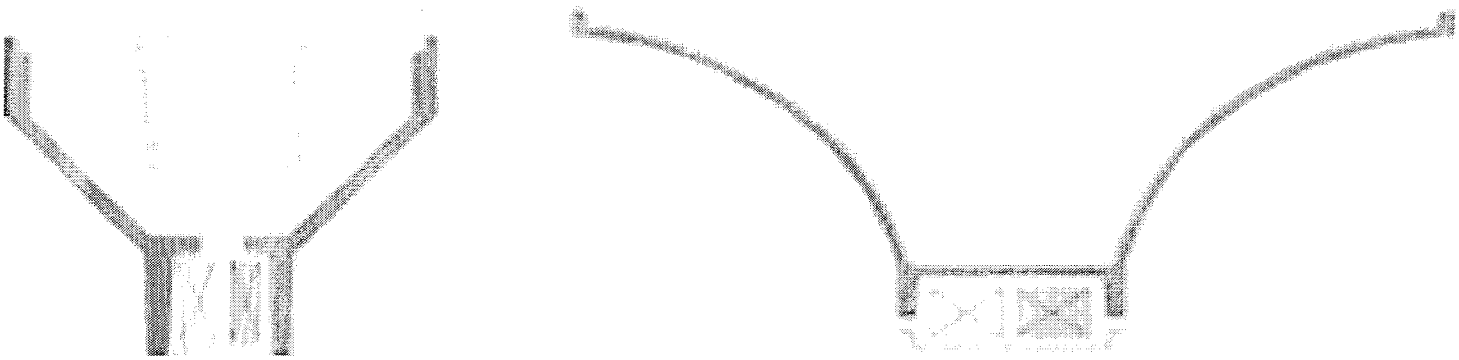

Fig. 9. Comparative sections of the Salk Institute's "folded plate scheme" (left) and the Kimbell roof shells as explained by Komendant. Two variations on a theme – an integrated section combining a long-span shell girder with mechanical services on a linear module.

[15] "Yet while it seems clear that Kahn understood from the outset that he was working with, to quote Brown, 'a direct, simple sparse shell of sturctural validity and integrity' and not a vault, the shell concept is not so cleanly implemented either, since many of the shells, in all including the final schemes, are quite short in span and therefore not much more than folded slabs." Guy Nordenson, "The Lineage of Structure and the Kimbell Art Museum," *Lotus 98*, 1998, 39-47. This quote is particularly insightful given the discussion below. Nordenson's article deserves credit for the explication of the vault as a gullwing structure as well.

[16] The auditorium stair, as well, occurs within the service zone, though this appears to be an artifact of the project's late change in size. It is interesting to note that the stairs from the rear, lower level lobby rise through this zone, such that one is confronted with the gullwing section upon entering the lobby space from below. Likewise, exterior stairs from the parking lot occur within the plan dimension of the service zones, suggesting that Kahn saw both of these elements as essentially secondary circulation. While this is at odds with the realities of arriving by automobile, it is well in line with Kahn's conception of the park entrance as the primary means of arriving at the building.

[17] "As to his work method-Kahn was considered by many fellow architects as a 'broker'...Kahn had very many creative excellent young architects in his office. Kahn had the ideas, these fellows worked it out and added their own ideas-Kahn mainly acted as critic in the development process." August Komendant, letter to William Harper, 10 Aug 1980. In August Komendant Archives, the University of Pennsylvania, Box 21, "August Komendant Correspondence."

[18] "Kahn's Museum: An Interview with Richard F. Brown." *Art in America* v. 60, no. 5 (Sept-Oct 1972) 44-48.

[19] Ibid.

[20] Ibid.

[21] Ibid.

[22] Ibid.

[23] "Abstract of Program for the Institute of Biology at Torry [sic] Pines, La Jolla, San Diego." N.D. In Box LIK-27, "Salk Institute for Biological Studies, La Jolla, California." Louis I. Kahn Archives, University of Pennsylvania.

[24] Louis Kahn, "Form and Design" in Allesandra Latour, *op. cit. 117.*