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"Farnsworth Sketch" by Japanese architect, Tadao Ando
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PHOTO CREDITS

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1. INTRODUCTION

The columns are fully exposed with the perimeter floor steel welded to their inside flanges. The floors are composed of three inch concrete precast panels with cast-in-place concrete infill and travertine panels as the finished floor surface; the roof precast concrete panels support built-up roofing materials (drainage, insulation, etc.). The house is clad with single-pane, full height glass panels on all four sides. A central utility core pierces through the floor and extends down into the ground, providing an access point for all utility services to/from the house.

The house’s location and interaction with the landscape is essential to Mies’s design. Situated approximately one hundred feet from the northern edge of the Fox River in an undeveloped prairie site, the house’s large glass panels provide a 360-degree view of the nearby water and surrounding lands. Mies’ design strips the structure down to its essential elements, making the house feel almost invisible and allowing its occupants to constantly interact with the river and surrounding fields.

The Farnsworth House has suffered from intense flooding over the years. This report provides an in-depth study of the three most feasible options to mitigate the flooding threats and the technical recommendations are provided by experts in the field of hydraulics and house raising/relocating. Solutions weigh the viability of elevating, moving and/or employing a hydraulic system. This report includes a description of each option’s strengths and weaknesses and project costs.

The scope of this study has been confined to investigating the feasibility of the proposed options. As such, the more conventional requirements of construction have not been discussed because it is assumed that these are perfectly feasible to accomplish. Among the latter considerations are types of foundations including shallow footings and mini- or micro-piles, dealing with the high permanent water table and the need to hold down elements that are below this level and to waterproof floors and walls, sump pumps, making the permanent below grade structure invisible from above grade, dealing with the forces of water flow and water-borne debris while the house is in the temporarily elevated position, etc. We would point out however that allowances for these items have been included in the final budget level cost estimates prepared for this report.

Designed by Mies van der Rohe in 1945 and constructed in 1951, the Farnsworth House (Figure 2) is a vital part of American iconography, an exemplary representation of both the International Style of architecture as well as the modern movement’s desire to juxtapose the sleek, streamline design of Modern structure with the organic environment of the surrounding nature. Mies constructed this glass box residence of “almost nothing” for Dr. Edith Farnsworth as a country retreat along the Fox River in Plano, IL. It continued to be a private residence for over 50 years until Landmarks Illinois and NTHP purchased it in 2003. Today it is owned and managed by the NTHP and the site is open as a public museum.

The house consists of two main parts: the main level and lower terrace. The main level, elevated five feet above grade, consists of a small covered exterior terrace and the house interior. The main level can be reached via a lower terrace which is elevated approximately three feet above grade. Twelve wide flange steel columns rise out of the ground and support the steel structure; six columns support only the main level, two columns support both the main level and lower terrace and four stub columns support the lower terrace.

Figure 2 (center column). Farnsworth at night
(Photograph obtained and reproduced with permission by NTHP)
2. EXECUTIVE SUMMARY

As can be seen in Figure 3 to the right, Plano has the highest risk of flooding in the Lower Fox Watershed region. The past fifty years have shown that this risk is real, and the flooding has evolved into an overbearing threat to the region and more specifically, the Farnsworth House. Action must be taken to ensure the iconic structure's survival.

In discussing the three options for flood mitigation with staff from the National Trust and a Technical Advisory Panel during the preparation of this report, it became apparent that Option A (Raising the House In-Situ) and Option B (Relocating the House) were not thought to have as much potential as Option C (Hydraulically Lifting the House) because both A and B require extreme adjustments to the site and landscape, including the loss of all existing trees in fill areas.

Thus, the focus of this study was directed to Option C, hydraulically raising the house temporarily during a flood event. The careful study and thorough vetting of this option has shown it to be perfectly feasible and reliable. The system that is proposed will be such that damage to the house will be averted from every conceivable sort of malfunction of the components. There is precedent for temporarily moving large structures on a regular basis, structures that are much larger than the Farnsworth House and in some senses, more critical (e.g. movable bridges, see Appendix). The system is quite simple to understand and at the same time possesses a certain elegance that does not detract from the iconic house that it is seeking to protect.

For these reasons, the authors of this report recommend that Option C be adopted.

Figure 3 (right). Lower Fox Watershed map identifying Plano has high flood risk (USGS, 2013).
3. HISTORY OF FLOODING

Mies had a careful understanding of the site’s hydrology, which influenced the design and site placement of the house. The Fox River was known to flood, so Mies located the house a certain distance (approximately one hundred feet) from the river and elevated the main floor approximately five feet above grade. However, just three years after construction was completed, the house experienced its first major flood, with water entering the house and reaching a height of two feet above the interior level. Little information is known from the four decades following; only minor flooding was documented in the area.

Flooding in the area has significantly increased over the past twenty years, influenced strongly by an increase in development in the surrounding area. In addition, levels of unprecedented flooding have been noted throughout the United States in the past twenty years, leading to revised flood risk maps and the establishment of a “new normal.” The most serious flood occurred in 1996, when several feet of water flooded the house interior. The following year, another flood entered the house and reached a height of a couple of inches above the main level elevation. In 2008, the house was flooded with approximately eighteen inches of water. This past year, 2013, saw two events worth noting. In March, significant water encroached on the property and flooded portions of the terrace. The following month, another rainstorm raised the water level to within inches of the main level elevation.

During the flood season, the executive director and his staff monitor the weather daily with the National Oceanic and Atmospheric Administration (NOAA) radio in the Visitor Center, emergency weather service alerts on iPhones, Kendall County Emergency Weather Alerts and Emergency Horns activated by local public safety agencies. Advanced warning of this imminent weather varies, but at a minimum, the staff is given a two hour’s notice to mitigate potential damage. Once there is a call to action, there is a team assembled to gather supplies stored at the site to bring to the house. All movable portions of the house are raised on milk crates, and all carpets and rugs are rolled up and placed on these elevated furnishings (Figure 4). Drapes are collected, bound and tied up high (Figure 5). Unfortunately, those immovable objects (the lower terrace, the main structure, the center wood console that includes the bathroom, closet and kitchen, and the utility shaft) cannot be protected, and these portions of the structure are left exposed to the rising water. Once the flood recedes (Figure 6), the staff quickly begins the drying process to prevent mold growth and irreversible damage to the collections.
4. BACKGROUND RESEARCH

The past two decades have shown that flooding is a significant threat to the historic finishes and interior of the house, as well as to the exposed structural elements which continue to deteriorate with each subsequent flood. Documentation shows that the average occurrence of a flood that breaches the house is every 15 years, but recent flooding has far surpassed this probability. This potential increase in flood levels and occurrences led the National Trust to hire WWE to assess the hydrology and flood risks of the house and surrounding lands. WWE published a report in 2013 which confirmed that peak discharges and the frequency of flood events have increased over the years (Figure 7). It is expected that the site surrounding the house will flood annually, and there is a 20% probability that flood levels will rise above the terrace level in any given year. The study conducted by WWE proved that the peak flows are increasing and as such, the property floods with greater frequency than it previously did. Historic precedent can no longer predict the occurrence of a flood and while Mies’ design intentions did elevate the house above the assumed 1951 flood lines, this height is not capable of protecting the house from rising water.1

The National Trust also hired TT to complete a preliminary feasibility study on ways to alleviate the threat to the house from flooding. TT’s report documents the existing design loads (Figure 8), analyzes the existing connections and initiates a cost/benefit analysis of several mitigation options. The main structural analysis deals with how the building, connections and foundations would behave if elevated above the current flood lines. TT determined that the house could be lifted an additional nine feet above grade before the existing structure could no longer resist the increased lateral (wind and earthquake) loads the building would experience once elevated. The foundations would need to be replaced (or at a minimum, retrofitted) depending upon a geotechnical investigation of the subsurface and soil stratum below the building.

Of the four options (allow the house to flood or make it watertight, elevate the house in place, relocate the house, apply a technology to elevate and then reset the house), the first creates too much of a risk for the existing structure; making the house watertight is being considered for the lower terrace, but this is not a long-term solution for the upper portion as it requires interventions and alterations to the original design.2

The National Trust requested that RSA prepare a more in-depth analysis of the three best scenarios based on the preliminary study provided by TT and the recommendations of the Technical Advisory Panel: (A) Elevate the house and terrace in situ with additional fill placed under and around the house, (B) Move the house to high ground on the site or move to a newly filled portion of the site close to the original location, and (C) Employ a hydraulic or mechanical system to raise the house temporarily just prior to and during the flooding. Throughout January and February 2014, RSA worked with Ashley Wilson of the National Trust, Darren Dichtm of GEI Geotechnical Consultants, and experts in the fields of excavation, site filling, house moving and hydraulics to flesh out the three options.

The National Trust supplied RSA with existing conditions information and previous reports. These included original Mies van der Rohe drawings (Figure 9, obtained from MOMA’s archives), the HABS documentation (obtained from the Historic American Buildings Survey and the National Trust’s archives), and a complete site survey. GEI Consultants completed three soil test borings at the end of January 2014 to determine existing soil conditions below the structure, provided recommendations for the replacement of the existing foundations, estimated settlement potentials, and provided site preparation recommendations associated with the three mitigation options.

1 Refer to Wright Water Engineer’s “Farnsworth House Flood Risk and Conceptual Mitigation Evaluation” report for additional information. 15 May 2013.
2 Refer to Thornton Tomasetti’s “TT Project No. C13103.00: Relocating/Elevating Study” report for additional information. 6 September 2013.
3 GEI’s “Geotechnical Engineering Report,” 18 February 2014, has been attached at the end of this report.
5. FLOOD MITIGATION OPTIONS: OVERVIEW

The three mitigations options under analysis in this report are realistic choices to remove the structure from the flooding threats it is currently experiencing. While some ideas appear to be more complex upfront, all solutions will involve a multifaceted process and construction sequence that require integral teamwork among all consultants.

Option A elevates the house and re-grades the landscape such that the house will be in its original location but above the flood levels. The work will involve exposing the existing foundations, temporarily jacking the entire structure so that the foundations can be demolished, and temporarily relocating the house off of its current footprint to the site can be re-graded. Nine additional feet of fill would be added to the site, new footings would be inserted to ensure an even bearing stratum beneath the building, and the house would be placed on top of these new foundations (at the new elevation). The remaining land surrounding the house would be re-graded to properly transition the site lines, vegetation and walkways. The central utility shaft would also be lifted and altered.

With this option, the house remains in its original location on the site and maintains its proximity to the Fox River. The majority of the work would revolve around landscaping with minimal work done on the structure. When completed, both the house and lower terrace will be raised above the assumed 100-year flood occurrence level, reducing (and most likely eliminating) their likelihood of being flooded in the future.

Option B would move the house from its present location to a new site uphill closer to the road, out of the flood plain (Figure 12). This would place the house some 400 feet farther away from the river than its present situation, a change that would alter the house's intended relationship to the Fox River. Furthermore, it relocates the building closer to the surrounding roads, exposing occupants to noise pollution and contradicting the very living experience for which Mies designed.

This option would require a substantial portion of the site to be regraded to create a relatively level area for the placement of the house. There is no level area currently large enough to place the house above the flood zone without being immediately at the road frontage.

The major disadvantage to this option is that it completely transforms the structure's interaction with the site and river. Re-grading will change how the structure and site were originally envisioned and will result in the loss of existing trees. As one stands in the house and looks southward, one will noticeably be elevated above the Fox River (Figures 10 and 11). Requiring an intense amount of fill soil, this higher elevation will also cut off visitors’ experiences with the boathouse and the feeling of physically interacting with the river.

Figure 10. Model of original elevation of the Farnsworth House (RSA, 2014).
Figure 11. Model of Option A showing the new raised elevation of the Farnsworth House (RSA, 2014).
“Sub-options” were investigated that are hybrid versions of Options A and B. One sub-option is that the house would be moved partially up the hill and fill would be added to raise it nine feet above the flood plan. That fill would then be sloped to the river. A second sub-option is to move the house partially up the hill and only add fill beneath the structure, to raise it above the flood plain. Both of these versions have all of the disadvantages of Options A and B, particularly the dissociation of the house from the river and the elimination of many existing trees. The fill would dramatically change the gentle grading of the site with a mesa-like projection sticking up. For these reasons these sub-options were not further explored.

In Option B, the scope would require that the house be lifted from its foundations similar to the description in Option A. However, once on the dollies, the house would then be transported to a new permanent, relocated foundation and set in place. Of course new concrete foundations and utilities, including a septic field, would be required. Finally, finished grading and landscaping would be accomplished.

Option C integrates a permanent hydraulic system into the building's foundation so that in the event of a flood, the house can be mechanically lifted above the flood lines and lowered to its original elevation once the flood recedes. A first potential solution investigated was a simple scissor lift but this did not demonstrate sufficient rigidity and stability in a lateral direction (Figure 13, next page). After much study and refinement, a system that combined steel truss linkages and hydraulics was selected. The scheme for Option C would begin similarly to that of Options A and B: the existing foundations would be removed and replaced. However, in Option C, the foundations would be replaced with a new concrete pit into which hydraulic cylinders would be affixed.
The house would be attached to a new concrete slab located below grade which would form the ceiling of the pit; the house and slab would be lifted together by means of hydraulic actuators (Figure 14). Much of the equipment for the hydraulic system could be located below grade in the pit (Figure 15). Refer to section 9 for a full description of this system.

The major advantage with Option C is that once the work is completed, the house will look and feel as it always has; all new structures will be hidden below grade until the mechanism is activated. The system would be a permanent solution that would directly attach to and become a part of the structure. The system as designed is completely reversible, albeit with a good deal of effort required to accomplish this.

In all three cases, retaining the original foundations is not advisable and attempting to re-use the existing footings is not practical. Installing new foundations in all instances ensures that the building is supported on an even bearing stratum, a design feature necessary to ensure uniform settlement and foundational support. Geotechnical testing revealed the site around the Farnsworth House contains a thin layer of soft top soil over a layer of stiff fill material that overlays approximately ten feet of medium to very dense silty sand and gravel. Bedrock was reached approximately fifteen feet below grade. Groundwater was encountered approximately six to seven feet below grade. GEI determined allowable bearing pressure to be around 4000 psf, slightly higher than the original footing design. Thus, new shallow foundations are suitable for the magnitudes of loads experienced at the building, but since bedrock is only fifteen feet from the surface, deep foundations (mini- or micro-piles) are also an option that would minimize potential settlement.

All three options require the lifting and (temporary or permanent) relocation of the house to prepare the site. Moving the house out of the construction zone makes pouring the foundation, re-grading and working easier, therefore, it is recommended that the house be relocated during construction.

Figure 16 on the following page shows the potential house relocations for each of the flood mitigation options. It should be noted that since flooding during construction is a possibility, the house will need to be temporarily relocated to the far north portion of the site for Options A and C (Figure 16 shows one possible location).
Figure 16: Site plan showing the potential temporary or permanent relocation of the house for each option (RSA, 2014).
6. HOUSE RAISING AND RELOCATING FOR CONSTRUCTION ACCESS

Existing houses have been lifted and relocated in America for centuries. Buildings are temporarily raised to add basements (Figure 17), alter surrounding grade, replace or strengthen foundations (Figure 18), etc. Structures of particular significance have been relocated via dollies or truck beds to preserve the structure as a whole (Figure 19). The practice has matured with advancing technologies but the basic process remains the same.

For the flood mitigation options in this report, the house will be completely removed from the site; thus, the house will need to be lifted and transferred to a mobile system that can carry it to a selected location (such as that shown in Figure 20). Refer to the Appendix at the end of this report for an inventory of recent house raising and relocation precedents.

To begin, all of the house utilities need to be shut off and capped. In most projects, the site would then be excavated to allow the placement of steel support beams beneath the building to transfer the structural loads off the existing foundations. Since the Farnsworth House structure is already elevated five feet above grade, these steel support beams can be placed directly under the perimeter channels of the house without requiring any excavation (Figure 21).

Figure 17: Photo of building being lifted to insert new basement (RSA, 2013).
Figure 18: Photo of building being lifted along waterfront to insert new foundations (RSA, 2013).
Figure 19: Photo of dollies being inserted beneath Hamilton Grange for relocation (RSA, 2013).
Figure 20: Photo of Hamilton Grange being relocated (RSA, 2013).
Figure 21: Image of support beams beneath the Farnsworth House (RSA, 2014).
These beams are supported on timber cribbing. The geotechnical review recommends the subgrade be over-excavated and backfilled with a well-graded granular material and crushed stone to create a proper bearing pad for the cribbing. Once the timber cribbing is in place, the existing foundations are demolished and removed from the site. Hydraulic jacks are placed at the center of the cribbing (Figure 22) and connected to a central control panel that contains a sophisticated unified jacking manifold that insures that all points on the house are being lifted an equal amount. Per the control panel, the jacks uniformly extend to engage the steel and lift the structure. With each lift, the cribbing extends and the jack is moved to a higher level of cribbing; the heights to which this cribbing can extend is impressive (Figure 23). A field construction team attends to each lifting point, monitoring the existing structure during the lifting process. They ensure uniform movement, extend the cribbing, and raise the jack with each level.

The cribbing will be extended to a height deemed necessary to properly move the house off its footprint. In the case of the Farnsworth House, the building does not have to be elevated much because the main floor and terrace are already elevated above grade three to five feet. Once the house is high enough, it will be transferred to a mobile system to relocate it. Dollies would be delivered and placed beneath the support beams (Figures 24 and 25). After the beams are clamped to the dollies, the cribbing is removed, and the house is relocated.
7. RAISING THE HOUSE IN SITU: OPTION A

In Option A the house would be temporarily relocated during construction but returned to its original location once the grade is raised nine feet above its current level. This raises aesthetic questions such as the relationship of house to the river under normal conditions and the massive regrading required to achieve this condition such that the transitions of grade were made to look “natural.”

First, the house would be disconnected from the original foundation and utilities, both incoming water, electrical and signal as well as outgoing sewage. Then the house would be moved to a temporary storage area somewhere on site, well out of the way of the heavy earth moving equipment. (The procedure for moving the house to a temporary location is described in Section 6.) Any large trees that were in the fill area would be removed. At that point a program to raise the grade by delivering clean fill from offsite would begin. Depending on the new design configuration between 10,000 and 20,000 cubic yards of fill will be required to raise the area around the house by nine feet. Two regrading schemes of many possibilities are shown (Figures 26 and 27).

If a normal dump truck is used to haul fill and its loose bulk capacity is 12 cubic yards, then between 800 and 1,600 truckloads of fill would be required. It is conceivable that larger trucks could be used, but the load capacity of the highways between the source of fill and the site must be considered. Thus, the fill operation could have a steady stream of truck traffic for over one month. At the site, there would need to be a large bulldozer plus a roller for compaction of the newly placed fill. The final layer of fill would be topsoil capable of supporting a grass cover crop.

Once the fill is placed, new foundations would be constructed at a level some nine feet higher than the existing foundations. With proper compaction under the new foundations, ordinary spread footings could be placed directly on earth, with concrete piers extending up to about two feet below the ground surface, similar to the original design. The house could then be transported back to its original site and affixed to the new concrete piers.

Likely all new utilities would be installed at this time, especially considering that the existing utilities are over 60 years old and have been buried for that duration. Thus, new water, electric and telephone lines would be brought down from the road and buried directly in the new fill. A totally new septic tank and septic field would be installed to handle waste water.

There would be extensive landscaping required to accommodate the new location of the house. For the first year there might be some local settlement of the fill adjacent to the house and steps that will require maintenance. The site circulation paths would have to be regraded and probably relocated, local landscaping such as flower beds replanted and trees replanted as required. Some accommodation would have to be made at the boathouse, either containing the new fill behind reinforced concrete retaining walls or demolishing the boathouse entirely.
8. RELOCATING THE HOUSE: OPTION B

Another possibility is to move the house from its present location close to the river to a higher existing elevation, far (to the north) from the river. The distance that the house would have to move is close to 400 feet from its present location. It is quite obvious that both Mies and Dr. Farnsworth regarded the proximity of the house to the river to be an essential feature of the design. It is presently only 100 feet from the edge of the river bank (Figures 28 and 29). Moving it some 400 feet would destroy much of the intimacy shared between the house and the river (Figures 30 and 31).

From a technical viewpoint, this solution mitigates damage from future flooding at a relatively modest cost. Section 6 describes the physical lift and move of the house. In this case, the house would be disengaged from its current concrete piers and footings, the utilities disconnected, the house raised and moved onto a series of dollies. Then the house and dollies would be connected to a tractor that would pull it uphill to the new location and to be reset on a new foundation.

There is no area at the upper reaches of the site that approximates the large flat area closer to the river. Thus a certain amount of regrading will be required no matter where the house is finally sited. At that time a new foundation would be constructed that closely mirrored the original – concrete spread footings resting directly on undisturbed soil a minimum of four feet below the ground surface, with short concrete piers stopping about two feet below grade. Then the house would be lowered onto the piers and the new finish grades established.

An entire new set of utilities would be required, including electric, water and telephone. But because the house is much closer to the road, the distances for these new lines is not significant. A new septic system would be required as well. A new landscape design would be installed connecting the house to the Visitors’ Center.
9. HYDRAULICALLY LIFTING THE HOUSE: OPTION C

The most desirable solution to mitigating damage due to flooding would be to raise the house temporarily during a flood event and then lower it to its original position once the flood threat has subsided. In that scenario, the relationship of the house to the river, in respect to both location on the site and elevation to the river, would be maintained. In both of the other options as described in Sections 7 and 8, one of these key relationships is violated.

At first glance one might say, "Lift the house when a flood warning is issued? That is ridiculous. You can't do that without breaking all the windows and damaging all of the finishes, etc., etc." The art and science of hydraulics today permits very sophisticated installations to solve all sorts of problems. There are fail-safe mechanisms to provide assurance and comfort that the system will perform as designed. There is precedent for the use of these systems in many fields of engineering design. Refer to the Appendix at the end of this report for an inventory of the use of hydraulics in structural design and architecture.

This report presents a carefully considered hydraulic solution to the problem that responds to all of the possibilities that might be encountered during a flood event. For this initial feasibility study, it is assumed that the lower terrace is permanently detached from the main house and will remain in its original position during a flood. This can be accomplished by placing an additional permanent support or two tucked under the terrace out of sight (Figures 32, 33 and 34). The lower terrace will be allowed to flood and after the flood event, will be cleaned of any debris or mud (Figure 35). A further assumption is that there would be ample advance warning of the need to raise the house so that a slow lift can be designed taking a couple of hours if necessary. This minimizes pump sizes and pressures.

Figure 32: Schematic elevation of existing structure (RSA, 2014).

Figure 33: Elevation of structure highlighting potential new lower terrace structure (RSA, 2014).

Figure 34: Schematic sections of conceptual terrace alterations (RSA, 2014).

Figure 35: Elevation showing main level raised while lower terrace remains and is allowed to flood (RSA, 2014).
The simplest version of a hydraulic solution would be to consider how an automobile is raised on a hydraulic lift in a repair garage (Figure 36). A single cylinder is employed to lift up to three tons of weight in a matter of seconds. While the car is in the elevated position, a safety strut is placed so that any loss of hydraulic pressure will not cause the cylinder to retract spontaneously.

Why not simply place eight hydraulic jacks, one under each of the eight columns of the house, and synchronize them to lift the house uniformly? Such synchronous systems are readily available using unified manifold systems, similar to those that will be used to raise and move the house as described in Section 6. The major problem with this scheme is that the eight columns are not rigidly connected to each other at their bases, but rather cantilever almost eight feet above their bases. Furthermore, to resist lateral loads from the wind and river current, the eight cylinders would act as extensions of those cantilevers. Most hydraulics manufacturers shy away from using their cylinders and gland seals as cantilevers, although it could possibly be done. Another disadvantage is that to remain in the raised position, the full hydraulic pressure would have to be maintained for the entire duration of the lift period which could be several days; any failure resulting in a pressure drop could be catastrophic. Finally, maintenance, repair or replacement of elements of the hydraulic system would require temporary shoring of the house.

The solution presented in this report is hydraulics coupled with static linkages. The system uses structural steel linkage trusses nine feet high that are horizontal in their original position (Figure 37) but rotate 90 degrees into a vertical position; the hydraulic actuators (also referred to as cylinders in the body of this report) are angled so as to push these linkages in a diagonal direction (Figure 38). When the house is fully elevated, the trusses act to resist lateral load perpendicular to the long face of the house while the hydraulic pressure in the axial direction of the diagonal cylinders resists lateral forces imposed against the short side of the house (Figure 39).
1. Disconnect utilities. Prepare to move the house off its present foundations temporarily by inserting carrier beams on wood cribs below. Shim tight to put load of house into wood cribs, excavate to the base of the steel columns (Figure 40) and disconnect the steel columns from the concrete piers.

2. Lift the house and relocate it northward. Refer to Section 6 for full description of relocating process.

3. Demolish existing concrete piers and footings.

4. Excavate for new foundations, and pour new concrete pit. The current thought for the pit is to pour it in a U-shape configuration (Figure 41). The higher ends of the slab will provide a proper base for mounting the truss linkages, reduce the amount of concrete used and minimize uplift pressure from the ground water. The deeper center section will house the hydraulic actuators (Figure 14), hydraulic fluid reservoir and various other supplementary parts of the system. All components will be waterproof, allowing the pit to flood when the system is activated and the house is raised. Pour eight new concrete piers on spread footings under the eight exterior columns. (Figure 41).

5. Install concrete support beams and receivers for the cylinder trunnions. Trunnions are cylindrical projections used as a mounting and/or pivoting point. A common example is that of a cannon. The shaft from which a cannonball is propelled must be allowed to pivot up and down for proper projection; a trunnion is a pin connection at the head of the shaft that allows the cannon to be connected to its base in such a manner that it allows the body to pivot about that pin. This is how the actuators are affixed to the concrete beams while still being allowed to swing/rotate as they push the trusses into position.

6. Install steel linkage trusses in their flat, horizontal position (Figure 42, concrete piers not shown for clarity). The linkage components can be treated with a corrosion inhibiting surface coating. The link pins will be 316 stainless steel and the bearings will be a Teflon impregnated composite that is suitable for submerged operation.

7. Pour a new 16-inch thick reinforced concrete waffle slab of approximately the same plan dimension as the footprint of the house plus the columns (Figures 43 and 44, concrete piers not shown for clarity). This slab will rest on the walls of the pit as well as additional piers under each of the eight columns. Embed connectors for the steel linkage trusses and the piston head rods in the bottom of the waffle slab.

8. From the pit, make all physical, hydraulic and electrical connections for the hydraulic system.

9. Install controls for the hydraulic system as well as an auxiliary emergency generator located remotely from the house and higher than the flood zone. Refer to the next pages for specific components of the system.

10. Install new underground electric service from road to house to power the hydraulic system.
11. Test the system to raise the concrete waffle slab alone without the house on it. When the system meets all of the criteria, move the house back to its original position on top of the concrete waffle slab and anchor the steel column base plates to the top of the waffle slab. Test again with the weight of the house on the slab.

12. Complete final grading and landscaping. Cover concrete waffle slab with earth to match surrounding grade.

13. Reconnect utilities such that they have flexible connections that can extend nine feet into the air when the house is raised.

Features of the hydraulic system are as follows:

A. The system configuration will be single point failure proof. That is, the system will be able to sustain a catastrophic failure of any single component without inducing a systemic failure resulting in damage to the structure.

B. The lifting system for the structure will consist of the following components and features:

- Hydraulic Actuators (Cylinders). These will be heavy duty mill type cylinders (Figure 45). All exposed surfaces of the actuator will be corrosion resistant and rated for submerged operation. The rod interface will be a spherical rod eye and the cylinder mount will be a front trunnion type. The trunnions will rotate on steel/plastic bearings that are designed to operate in submerged conditions. Preliminary designs call for hydraulic actuators with 182” stroke and a 10” bore. The nominal operating design pressure will be 1500 PSI. The actuators will be rated for 2100 PSI operation. End of stroke metering will be provided should catastrophic loss of hydraulic fluid be encountered, allowing the flow of fluid to be immediately capped off.

- The anticipated minimum life expectancy on all seals is approximately seven (7) years. Longer life is likely. The piston seals (gland seals on Figure 45) life expectancy is affected by the condition of the piston rod surface. Rod surfaces that are damaged can abrade the seal and result in premature seal failure. There is a remote possibility that heavy floating debris may impact a rod during a flood with sufficient force to inflict damage. It is recommended that all rods are inspected prior to lowering the structure. If rod damage is observed or suspected a qualified technician will be able to perform a field repair.

- The actuators will have internally mounted linear transducers such as magnetostrictive, LVDT or other suitable type. Transducer signal will be either 4-20mA or 0-10VDC.

- Pistons will provide end of stroke metering to effect a hydraulic cushion.

- Critical control valves will be close-coupled or internally mounted to both ends of the cylinder. By avoiding hose or pipe connections for these valves, reliability is greatly enhanced.

- All actuators (cylinders) will operate off of a single common Hydraulic Power Unit (HPU). The HPU will have two (2) pump/motor arrangements; a primary pump and an auxiliary pump.

  - Primary Hydraulic Power Unit (HPU) consisting of a motor and pump assembly. The motor is likely to be in the range of 5 horsepower (Figure 46). With facility power, all actuators will be powered from the primary pump. This will be considered normal operation. The total rise time with facility power will be less than two (2) hours.

  - Auxiliary Hydraulic Power Unit consisting of a much smaller pump to serve as a back-up to the primary HPU. In the event of a facility power loss situation the smaller auxiliary pump will raise the structure while operating off of the back-up generator.

  - The back-up generator should be capable of running the auxiliary pump, the control system and limited auxiliary lighting. Preliminary calculations indicate that a 1.5 HP motor will be able to raise the structure nine (9) feet in less than six (6) hours. For this capacity a 2.5 kVA generator should suffice. Generators with this output will have total dimensions in the 24” x 34” x 24” range. There may be other considerations that will affect the generator selection, e.g. fuel storage. Most small generators are gasoline operated. LP or diesel operation may be preferred and that criterion may determine the
The generator needs to be sized to operate the primary pump, we would require a 7 kVA unit.

- Valving consists of overall control valves that direct and regulate the hydraulic flow to the main lines, proportional control valves located on or in each of the actuators that are capable of reading feedback from sensors in order to meter the flow and thus control the speed of the piston head, load-holding valves that act like check valves with zero leakage of hydraulic fluid to “lock” the piston head into a final position, pilot operated check valves to be able to open the load-holding valves when it is desired to resume movement and counterbalance valves to limit a “hard stop” should there be a malfunction during operation. All of these are part of the built in reliability of the system.

- Conduit (steel tubing, hoses, fittings) with waterproof capability. The hoses are rubber coated and highly resistant to corrosion. The hydraulic actuator piston rods will be hard chrome plated. Chromium is virtually impervious to rust and corrosion that would normally be precipitated by submerged operation.

- Accumulators that store small amounts of hydraulic fluid that might be needed to supply the pilot operated valves.

- Sensors that will be able to track, monitor and feed information on location and attitude of the house during up and down movement operations, conditions of various valves (whether they are open or closed), current draw on the motor, etc.

- Electrical Control System that will be programmed to operate the entire hydraulic assembly without need of human input. An industrial programmable logic controller will provide the “brains” of the system. These controls can be viewed remotely via computer screen wherever it may be desired to show them and a touch screen interface will be provided.

- Festoon arrangement will allow movement of certain hoses and cables as the lifting operation is proceeding. Some accessories will be close-coupled so that they do not move with respect to their base but others must be able to accommodate movement.

C. On command, a hydraulic power unit will supply high pressure fluid to control valves mounted in close proximity to eight hydraulic actuators (cylinders). The actuators will be located under the structure. Each pair of actuators will operate a link arm that will pivot from near horizontal position to slightly past vertical. The actuator/linkage system will displace a rigid support substructure, the concrete waffle slab, with the Farnsworth house mounted above.

D. An “UP” command will result in the control valves porting fluid to the cap end of the hydraulic cylinder (Figure 47). This will extend the piston rods and raise the structure. The spherical rod eye will eliminate any bending from the structure above being introduced into the actuators; all loads will be in axial compression. Additionally, the UP command will control pilot pressure to close-mounted counterbalance valves located in the rod end of the cylinders to maintain a controlled raise sequence and react against any overhauling forces generated by wind load. Since a rapid response is not required, the raise sequence will be designed to take approximately two hours.

E. A “DOWN” command will result in the control valves porting fluid to the rod end of the hydraulic cylinder (Figure 47). This will retract the piston rods and lower the structure. Additionally, the DOWN command will control pilot pressure to close-mounted counterbalance valves located in the cap end of the cylinders to maintain a controlled lower sequence and react against any overhauling forces generated by wind load. Since the lowering time is not of importance, the lowering sequence will be designed for a two hour duration.

Figure 47: Simplified Hydraulic Fluid Flow for Raising and Lowering Structure (C. Valenze, 2014).
F. Linear transducers that recognize and measure movements of the piston head in all directions would be internally mounted in the actuators and will provide feedback for closed loop control to maintain synchronized actuator movement. In addition to position monitoring, selected structural components may be strategically instrumented with strain gages and/or inclinometers. These will report to a separate monitoring system. In the event that excessive stress or an errant attitude is detected all lifting or lowering motions shall stop.

G. When the actuators are fully extended the mechanical linkage will go slightly over-center and against hard stops. The links will be mechanically locked in this position. This will permit the structure to remain in the raised position indefinitely without hydraulic pressure. This will also permit maintenance or removal of the hydraulic actuators.

H. The design goal is to have a system that requires the same skill set as one would need to select the proper elevator button (i.e., up or down). The system will be completely automated for normal operation requiring only the selection of an up or down push button. A keyed switch or keypad code activation is possible to prevent inadvertent operation by unauthorized personnel. There will be a status display for qualified maintenance technicians. Additionally, if a dedicated phone line is available, remote operation (raise only) and troubleshooting will be possible.

I. As envisioned this system will require very little maintenance for the duration of its service life. Normal annual maintenance will be off-line fluid filtering, filter replacement, hose replacement (as needed). A design life of 750 cycles (3000 hours of operation) is anticipated. The system should be exercised regularly. A walk around inspection is recommended each time the system is raised. This can be completed by any caretaker with minimum training. That inspection will primarily look for fittings or hoses that may have slight leaks. If leaks are detected a qualified hydraulic technician should be called to repair or replace the defective fitting. In the event that a pump, motor, valve or other minor component requires repair or replacement a single qualified technician will be able to perform that work in the field. Replacing or repairing the hydraulic actuators will involve a qualified team and equipment suitable for lifting the actuator.

J. This system is designed for maximum reliability. As was stated above, its configuration will be single-point-failure proof; that is, it will possess sufficient redundancy that, should any single component fail, there will be no damage to the house. The design of the system prevents systemic failure due to a single component failing. The most vulnerable part, the hydraulics, has safety features at each level via the arrangement of valves as described above and of monitoring sensors. There is even an auxiliary hydraulic pump for the main system and a full power backup via an emergency generator should there be a failure to supply from the local power company.

The hydraulic actuators that are proposed for the project are intended to be used in a submerged state as are all of the valves and connectors. These components will be below grade (Figure 48) and are industry tested for these conditions. There is a tremendous precedent for using hydraulic systems in harsh and submerged applications. Hydraulic components including actuators, valves and HPUs find extensive use in a broad spectrum of marine applications. Off shore oil rigs, ocean going vessels and dock side support equipment all employ hydraulic actuators for many critical applications.

The feature of the steel linkage trusses is an enormously powerful reliability tool. Once in the fully raised position (Figure 49), these trusses are designed to carry the full vertical load of the house, without any reliance on the hydraulic actuators. Thus, if for some reason the pressure is reduced in one or more actuator, this will have no effect on the vertical stability of the house.

As part of the system operations, a regular schedule of testing will be specified. While emergency generators require periodic testing to ensure their reliability, so too will the hydraulics need to be tested on a predetermined schedule. (Parenthetically, we cannot resist suggesting that this scheduled maintenance lifting can be made into an ‘event’ to be celebrated regularly at the house.)
10. COST ESTIMATES AND PROJECTED SCHEDULE

Cost estimates were prepared using budget level techniques. In many cases estimated quantities of materials have been included but in other instances, items have been priced on a lump sum basis. Costs for a general contractor (i.e. 10% for General Conditions, 10% for Overhead and 10% for Profit) have been added to the basic trade costs and are included in the final reported costs. Estimated costs at budget level are normally on the generous side and therefore, no additional percentage for contingencies has been added.

Option A: $2.4-$2.9 million: Elevate the house and terrace in situ with additional fill placed under and around the house. A large quantity of fill would be imported to regrade the site. As a minimum, approximately 10,000 cubic yards of fill would be needed. Fill is usually supplied from the spoils of other construction sites, but the rural location likely means the fill will be locally excavated. For purposes of this exercise, we picked $100 per cubic yard, to furnish, haul place, compact, grade and seed the fill. At that cost for fill, the price range for Option A would vary between $1.8 million and $3.1 million depending on the quantity of fill, the lower number representing 10,000 cubic yards and the higher number representing 20,000 cubic yards.

Option B: $300,000-$400,000: Relocating the house to high ground on the site, is by far the least expensive of the three options as it involves simply moving the house to a new foundation and connecting new utilities.

Option C: $2.5-$3.0 million: Employing a hydraulic system to raise the house temporarily just prior to and during the flooding, has the most components for which costs must be estimated. The hydraulic system is comprised of all normal components (pumps, valves lines, controls) and does not require inventing any new technologies. The estimated cost shown is the result of careful study of both the structure and the equipment that would be required.

The authors of this report recommend Option C and have developed a conceptual design and construction schedule for this option (Figure 50).

| FARNSWORTH HOUSE - DESIGN AND CONSTRUCTION SCHEDULE FOR OPTION C (HYDRAULICS) |
|---------------------------------------------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Design                                                       | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Select CM                                                     | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Order long lead items                                        | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Modular - office and on site                                 | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Fabricate steel                                              | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Move existing house                                          | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Excavate and dewater for pit                                 | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Foundations and Concrete                                     | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Site utilities                                                | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Ramp, roof (tent)                                            | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Install hydraulics                                           | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Install controls/prelim testing                              | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Pour waffle slab                                             | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Move house back onto slab                                     | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Test/accept hydraulics (Final)                               | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Clean/fit out House Interior                                 | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |
| Finished landscaping                                         | August                 | September              | October                | November               | December               | January                 | February               | March                  | April                  | May                    |

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