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EVALUATION OF WMCO FOAM ALTERNATIVES

04/26/88

IT CORP.
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REPORT

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INTERNATIONAL
TECHNOLOGY
CORPORATION

RESPONSIVE TO THE NEEDS OF ENVIRONMENTAL MANAGEMENT

[redacted]

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INTERNATIONAL TECHNOLOGY CORPORATION

EVALUATION OF WMCO FOAM ALTERNATIVES

Regional Office
312 Directors Drive • Knoxville, Tennessee 37923 • 615-690-3211

IT Corporation is a wholly owned subsidiary of International Technology Corporation

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WMCO recently requested that IT Corporation (IT) and ASI examine combinations of rigid and flexible foam in addition to the combination studied in August 1987 as detailed in the attached report, "Structural Assessment K-65 Storage Silos Radon Mitigation and Dome Reinforcement." The purpose of this letter is to discuss the structural effects of the combinations on the K-65 silos and the concerns related to foam reaction temperature.

The questions asked by WMCO and the responses prepared by IT and ASI are as follows:

Question 1:

What is the minimum amount of flexible foam that can be applied in each silo and still provide the structural support for the 20-foot weakened center section? Will the following design work? (Reference Attachment 1.)

Response:

The configuration depicted in Figure 1 of Attachment 1 was analyzed and the following conclusions were made based on the assumptions listed herein. (Reference Figure 1 of Attachment 2, which depicts recommended foam layers.)

1. For this configuration, a minimum layer of flexible foam (3 feet thick) is required to maintain the expected loading on the dome within acceptable limits as a result of rigid foam expansion. This type of loading is assumed to be a one time event, and once cure of rigid foam is complete, these loads will become negligible.

2. For this configuration, the loading on the dome due to seasonal temperature variations (thermal movement) is expected to be less than those produced by rigid foam expansion during initial cure. This type of loading is expected to be cyclic and not additive to the expected

loading due to initial rigid foam cure. If the dome is foamed in the summer, the maximum load of this type is expected to occur during the winter months when the dome contracts.

3. If the dome collapses, the dome would be maintained in its approximate position with this foam configuration. A settlement of approximately 2 inches is expected with a 3-foot layer of flexible foam.

4. If the center portion of the dome collapses, the structural integrity of the remaining portion of the dome is questionable. The configuration depicted in Figure 1 of Attachment 1 does not provide support for the outer portion of the dome.

5. Implementation of the foam system does not necessarily prevent advanced cracking of the dome or even dome failure. It is recommended that additional weight be kept off the 30-foot center portion of the dome during the foaming operation.

6. If contact between the rigid foam layer and the dome is not maintained for any reason, no structural support is provided.

7. An uncertainty exists concerning the flexible foam when it is used for this particular application. The compressive modulus of the flexible foam may possibly change over time, which is known as "compression set." Because this is a new application for flexible foam, quantitative data do not exist; further investigation of this phenomenon (conducting tests) is recommended.

Conclusions and concerns related to foam reaction temperature are discussed in Question 4.

Discussion:

1. <u>Assumptions Made In This Analysis</u>

The calculations performed to determine the effects of foaming used the following specific assumptions:

- Maximum volumetric expansion of rigid foam is 6 percent.
- Compressive modulus of flexible foam is 0.9 pounds per square inch (psi) at 25 percent defection, and it exhibits a linear relationship between 0 and 25 percent deflection.
- Density of rigid foam is 2 pounds per cubic foot (pcf).
- The flexible foam does not expand during cure.

The projected dome loading is particularly sensitive to the maximum volumetric expansion of the rigid foam and to the assumptions made concerning the compressive modulus of the flexible foam. If the volumetric expansion of the rigid foam during application of the foam is higher than the value assumed in the calculations, the resulting upward forces on the dome will be higher. If the compressive modulus of the flexible foam is higher than the value assumed in the calculations, upward forces on the dome will become greater.

References (Kirk-Othmer Encyclopedia of Chemical Technology, 3rd Edition, Attachment 6) suggest that a relationship exists between density and compressive strength (measured by tests such as ASTM D1621) for flexible open-celled foams. Information provided by Foam Enterprises indicates a compressive modulus of 0.9 psi for the particular brand of flexible foam chosen for the original design. Test data should be obtained to confirm this assumption. If test data yield a significantly different value, the flexible foam layer thickness should be adjusted accordingly.

Adequate controls are required during foam application to ensure that the assumed properties of the flexible foam are obtained. If a variation in these properties is anticipated, then the upper limits must be defined and considered prior to the foaming operation.

2. Expansion of Rigid Foam and Resulting Loads on the Dome

Assuming instantaneous maximum vertical expansion of both rigid foam layers, a 3-foot layer of flexible foam results in an upward force on the dome of 41 pounds per square foot (psf) (see pp. 48-50 of Attachment 3), while a 2-foot layer of flexible foam results in an upward force not to exceed 67 psf (see pp. 44-48 of Attachment 3). The dead weight of the dome is approximately 26 psf acting downward. One of the objectives of this project is to maintain the structural integrity of the dome; therefore, the dead weight should not be substantially exceeded. A 3-foot layer of flexible foam is recommended based on the listed assumptions, and the lower layer of rigid foam should be allowed to cure before the flexible foam is applied.

3. Loading on the Dome Produced by Seasonal Temperature Variations (Thermal Movement of Dome)

At the maximum assumed delta temperature of 140°F (120°F maximum summer temperature to a minimum winter temperature of -20°F), the maximum dome movement is 1.26 inches (see Page 28, Attachment 3). The calculated loading on the dome due to the maximum dome movement is 18 psf when a 3-foot layer of flexible foam is used. The calculated loading for a 2-foot flexible foam layer is 27 psf. Because these loadings are approximately equal to or less than the dome dead weight of 26 psf, adverse effects to the dome are expected to be minimal.

Question 2:

Since a 2- to 2½-foot layer of flexible foam will be applied under the rigid foam supporting the 20-foot weakened center section of the dome, can the same design be used for the entire silo dome for each silo? Will the following design work? (Reference Attachment 1.)

Response:

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Answer to Part 1 of Question 2

Silo 1 contains approximately 20 feet of residue; Silo 2 contains approximately 22 feet of residue. Calculations are based on conditions in Silo 1 and are expected to produce a larger loading on the dome for any given flexible foam layer thickness. Silo 1 contains a greater depth of rigid foam. The greater depth of rigid foam results in increased linear expansion and higher upward forces. (Reference Attachment 3 for these calculations and Figure 2 of Attachment 2.)

Answer to Part 2 of Question 2

The following conclusions were made based on the calculations and the same assumptions stated for Question 1. Note that the configuration in Question 2 differs from the configuration studied in the original Structural Assessment Report prepared by ASI and provided in Attachment 4. Therefore, the analysis of this configuration is more limited than that of Question 1.

The conclusions for Question 2 are as follows:

1. For this configuration, a minimum layer of flexible foam (3 feet thick) is required to maintain the expected loading on the dome due to rigid foam expansion within acceptable limits. Again, this type of loading is assumed to be a one time event.

2. The loading of the dome due to seasonal temperature variations (thermal movement) is more complex than that discussed in Question 1. This is because the rigid foam layer is continuous under the dome and has a varying cross section. Also, the maximum vertical dome thermal movement occurs at the dome center and decreases in the outer region of the dome. If the foam configuration depicted in Figure 2 of Attachment 2 is chosen based on other factors, further study of dome thermal movement is required.

3. Conclusion Numbers 3, 5, 6, and 7 made in response to Question 1 also apply to Question 2.

Discussion:

1. Assumptions Made in this Analysis

The assumptions used in response to Question 1 also apply to Question 2.

2. Expansion of Rigid Foam and Resulting Loads on the Dome

The loads calculated for this configuration do not include expansion of the 3-foot layer of rigid foam on top of the K-65 residue. This is justified based on the conclusions of Question 4. A 3-foot layer of flexible foam results in an upward force on the dome of approximately 23 psf (see Page 54 of Attachment 3), while a 2-foot layer of flexible foam results in an upward force of 40 psf (see Page 55 of Attachment 3).

The dead weight of the dome is approximately 26 psf. Because one of the objectives of this project is to maintain the structural integrity of the dome, the dead weight should not be substantially exceeded. Therefore, a 3-foot layer of flexible foam is recommended based on the listed assumptions, and the lower layer of rigid foam should be allowed to cure before the application of the foam layer.

Question 3:

Can a gel (previously studied) replace the flexible foam in the original design for each silo or in the above two designs?

Response:

The gel is an incompressible material that could possibly concentrate the weight of the foam above the gel to the silo walls over a relatively small area and is therefore not recommended.

Question 4:

If the original design is used for each silo:

(a) How exothermic is the flexible foam?

(b) How slow should the flexible foam be applied and what method (e.g., layered)?

(c) How fast will the heat build up in each silo?

(d) Will the heat buildup in the silo and inside the foam layers affect the foam and/or concrete walls/dome?

The current design consists of a base layer of rigid foam, an intermediate layer of flexible foam, and a top layer of rigid foam. The base layer of rigid foam is used as both a sealant for radon gas and a structural base for the additional layers of foam. The depth of the rigid foam layer should be such that it does not exceed the straight sides of the silo after expansion. The intermediate layer of flexible foam will be approximately 3 feet thick and allow for the expansion of the rigid foam as well as seasonal and daily expansion of the silo itself due to temperature fluctuations. The top layer of rigid foam is intended to support the central dome area of the silo.

Response 4(a):

The exothermic heat of reaction for flexible foam is 24 Kcal/mole. (Reference Attachment 5.)

Discussion 4(a):

In contrast to the rigid foam, flexible foam dissipates reaction heat quickly to the ambient air due to its open cell structure (reference thermal conductivity data in Attachment 6). Dave Dressel of Foam Enterprises stated that from the ambient temperature of 75°F the maximum resultant foam temperature reported for the flexible foam is about 140°F, or a

delta temperature of 65°F. The temperature rise occurs within 5 to 10 minutes of application. He stated that the thermal degradation temperature of the flexible foam is approximately 200°F.

Response 4(b):

Per vendor recommendations the flexible foam should be fabricated continuously in layers not to exceed 5 feet in depth during each layer application. There should be a 4- to 8-hour cooling period prior to application of additional layers as required.

Response 4(c):

Rigid foam conducts heat slowly; flexible foam conducts heat readily. Heat capacity data on rigid foam are provided in Attachment 6. The heat of reaction should not differ significantly from that of flexible foam, 24 Kcal/mole, per Attachment 5. Per vendor information, the maximum projected surface temperature for the concrete silo would be 120°F. Exactly how fast the heat would build up and dissipate would be a function of the application rate as well as the physical properties of the foam. The application rate depends on the injection equipment of the vendor, as yet not specified. Insufficient information is available to model the system.

Discussion 4(c):

Per Dave Dressel of Foam Enterprises, a test was performed with a 10-foot cube of rigid foam. Thermal measurements at the core indicated a temperature drop of 1°F per hour, requiring 7 to 10 days to cool the entire mass to an ambient temperature of 75°F. Based on this information, maximum core temperature must have ranged from 243 to 315°F. The vendor confirmed that the maximum foam temperature reported for rigid foam is 290°F. Foam Enterprises also applied rigid foam inside a steel vessel; the maximum surface temperature was reported to be 120°F. The low surface temperature resulted from the rapid cooling of the outer surface layer of the foam and the steel vessel, combined with the slow transfer of heat resulted from the inner core due to its high thermal insulating value. A similar heat

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transfer profile would be expected within the concrete silos. Based on the vendor-supplied data, the foam core temperature may reach 290°F; the surface temperature would not be expected to exceed 120°F.

As stated in the discussion section of 4(a), flexible foam dissipates heat quickly because of the open cell structure. With proper air circulation in the silo, the reaction heat is not expected to build up beyond that as a result of the rigid foam reaction.

If a substantial temperature rise is detected during application in either the rigid foam or flexible foam applications, the rate of application could be reduced. A method of detecting surface or internal temperatures within the silo during foaming should be investigated.

Response 4(d):

Based on the temperatures discussed in response to Question 4(c), and with proper application of the base layer of rigid foam and the intermediate layer of flexible foam, thermal degradation of these two foam layers should not occur and there should be no adverse impact to the concrete silos.

Discussion 4(d):

1.0 Thermal Impact on the Foam

Large quantities of rigid foam are commonly formed in one continuous application without difficulty (i.e., barges) according to the vendor. The vendor stated that with proper formulation of the rigid foam, there is no danger of any type of thermal degradation. He states that from an ambient temperature of 75°F, the maximum resultant foam temperature reported for the rigid foam reaction is 290°F, or a delta temperature of 215°F. The temperature rise occurs within 10 minutes of application. There is no danger of exceeding the rigid foam critical degradation temperature of 305°F. Heat dissipates quickly from the rigid foam surface. With an adequate cooldown period between application of the flexible foam,

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the interface between the foam layers should remain intact. The flexible foam layer should be applied per the response to Question 4(b).

The application of the final layer of rigid foam on top of the flexible foam layer presents the greatest thermal concern. The interior temperature of a large volume of rigid foam may rise as high as 290°F, while the flexible foam has a degradation temperature of about 200°F. The concern is that in the rapid application of the final layer of rigid foam (during the initial 10 minutes of reaction) the high temperature may cause thermal degradation of the flexible foam surface at the interface. The vendor stated that he has no experience with forming rigid foam on top of flexible foam and added that one could only speculate what might happen. Limited experimental testing may be required. One test discussed with the vendor was to fill a large cardboard box (e.g., a 4-foot cube) halfway with flexible foam and allow it to cool. The remaining space in the box then could be filled with rigid foam. After cooling, the box could be cut vertically in half to determine the effect of the rigid foam on the flexible foam. A thermocouple to monitor the temperature could be placed in the center of the surface of the flexible foam before adding the rigid foam.

2.0 Thermal Impact on the Concrete

Based on the information from Foam Enterprises discussed in Question 4(c), the maximum silo surface temperature expected is 120°F. A temperature of this magnitude is not anticipated to be a problem with the concrete silos. Concrete structures routinely are exposed to temperatures of this degree during the summer months.

Question 5:

Can the flexible foam be eliminated completely? Can each silo be filled with just rigid foam and leave a cavity for the expansion of the rigid foam? Will the following design work? (Reference Attachment 1.)

Response:

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This type of configuration is not recommended because (1) there is no flexible foam to absorb the vertical component of the expansion of the rigid foam during cure, and the expansion of rigid foam would probably cause failure of the dome; and (2) this configuration would restrict dome thermal movement, possibly to the point of causing failure.

Recommendations:

Test data should be obtained on the final foams selected to verify the assumptions made concerning physical properties in the calculations.

- Additional investigation of compression set of flexible foam should be undertaken by conducting tests or obtaining test data.
- Results of the tests should be studied to determine if any design changes are required.
- A conservative application approach, without further experimental study, would be to allow adequate cooling of the bottom rigid foam layer of a day before application of the flexible foam layer, and to allow adequate cooling of an additional 6 days before application of the top rigid layer. The upper layer of rigid foam must be applied in quantities small enough that the upper flexible layer is not degraded. At the present state of the art, this latter quantity needs to be determined by actual measurement during a bench-scale test.

Attachments:

Attachment 1 - Questions To Be Resolved

Attachment 2 - Foam Configurations

Attachment 3 - Calculations

Attachment 4 - Structural Assessment K-65 Storage Silos Radon Mitigation and Dome Reinforcement

Attachment 5 - Trip/Telephone Report - Heat of Reaction

Attachment 6 - Physical Properties of Rigid and Flexible Foams

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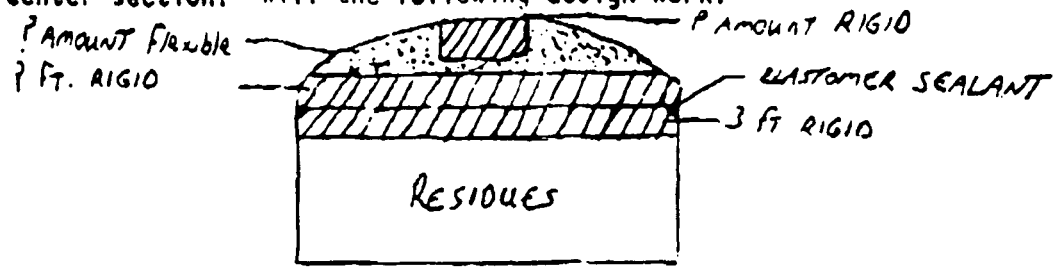
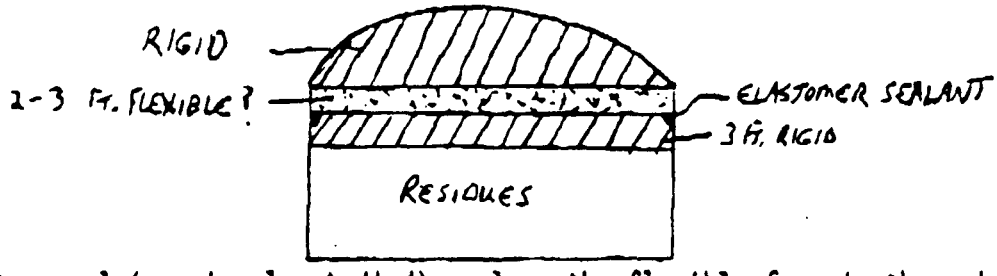
QUESTIONS TO BE RESOLVED

1) What is the minimum amount of flexible foam that can be applied in each silo and still provide the structural support for the 20 foot weakened center section? Will the following design work?



2) Since a 2- 2 1/2 foot layer of flexible foam will be applied under the rigid foam supporting the 20 foot weakened center section of the dome, can the same design be used for the entire silo dome for each silo? Will the following design work?

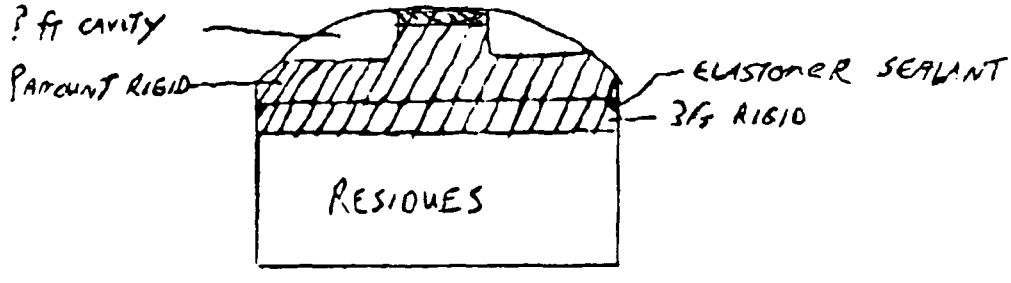


3) Can a gel (previously studied) replace the flexible foam in the original design for each silo or in the above two designs?

4) If the original design is used for each silo:

   a) How exothermic is the flexible foam?
   b) How slow should the flexible foam be applied and what method (e.g. layered)?
   c) How fast will the heat build up in each silo?
   d) Will the heat build-up in the silo and inside the foam layers affect the foam and/or concrete walls/dome?

5) Can the flexible foam be eliminated completely? Can each silo be filled with just rigid foam and leave a cavity for the expansion of the rigid foam? Will the following design work?



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ATTACHMENT 2
FOAM CONFIGURATIONS

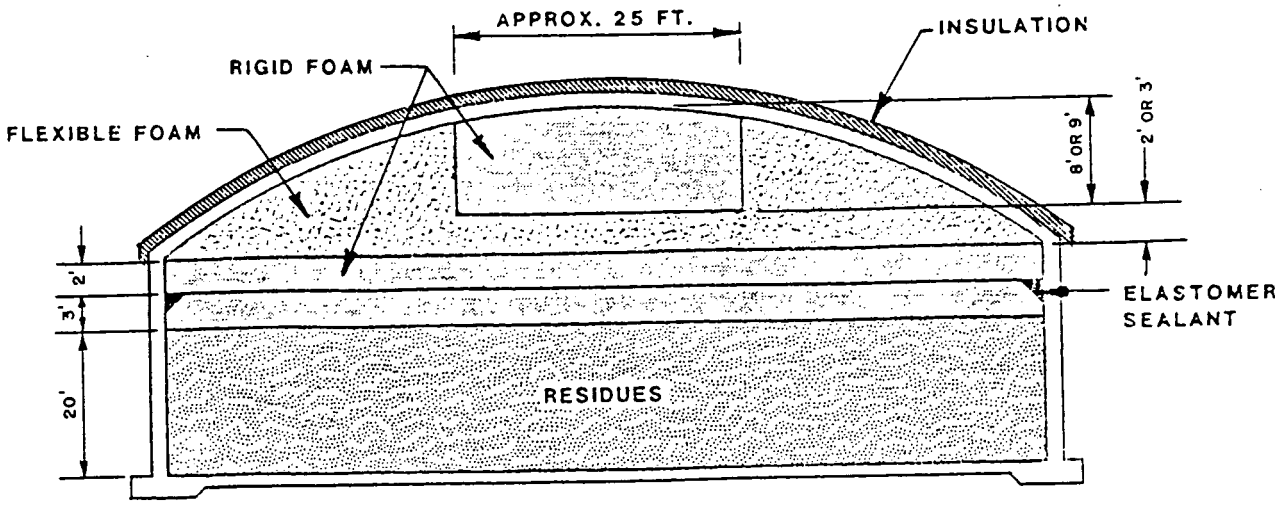

FIGURE 1

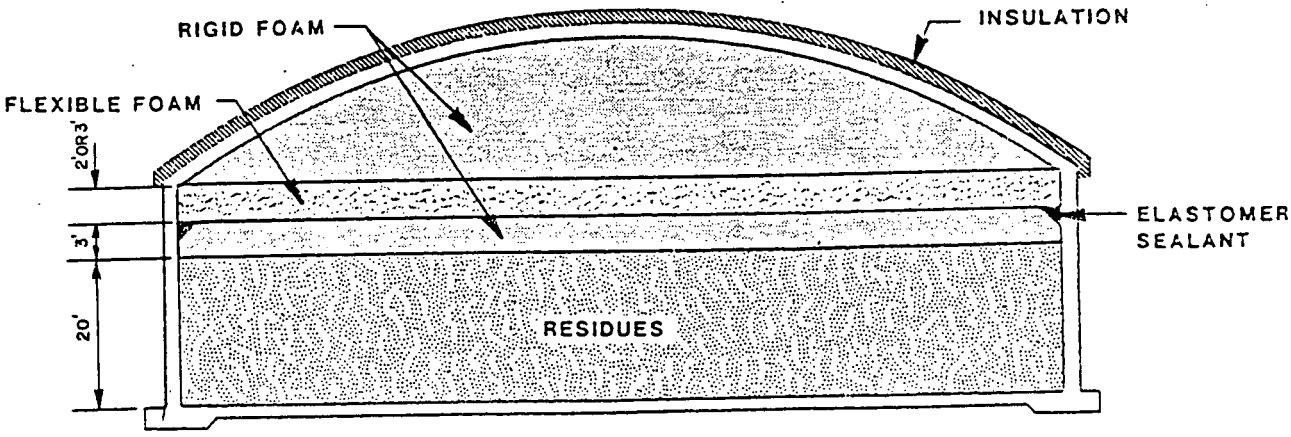

FIGURE 2

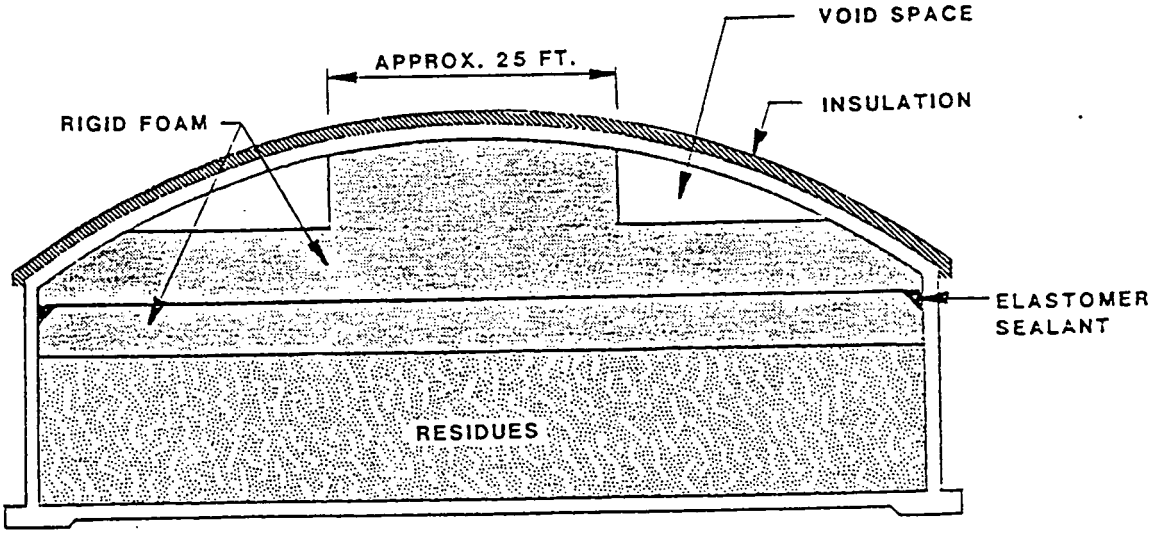

FIGURE 3

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CALCULATION WORKSHEET

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

PURPOSE

THE PURPOSE FOR THIS CALCULATION IS TO INVESTIGATE THE STRUCTURAL BEHAVIOR OF THE K-65 CONCRETE SILO WHEN FILLED WITH A COMBINATION OF FLEXIBLE AND RIGID FOAM IN THE REGION BETWEEN THE CONTENTS AND THE DOME. THE EFFECTS OF THE ADDED WEIGHT OF THE FOAM ON THE SILO, PLUS THE EFFECTS OF THE FOAM ON DOME THERMAL MOVEMENT ARE EXAMINED, AS WELL AS THE ABILITY OF THE RIGID FOAM TO SUSTAIN LOADS.

STATEMENT OF PROBLEM

DETERMINE THE EFFECTS OF ADDING A COMBINATION OF RIGID AND FLEXIBLE FOAM ON THE K-65 CONCREE SILO.

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SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

REFERENCES

1) MARKS' STANDARD HANDBOOK FOR MECHANICAL ENGINEERS
Editors - BAUMEISTER, AVALLONE, BAUMEISTER
8th EDITION (McGRAW - HILL)

2) PRINCIPLES OF HEAT TRANSFER
FRANK KREITH
3rd EDITION (HARPER & ROW)

3) THERMAL ENVIRONMENTAL ENGINEERING
JAMES L. THRELKELD
2nd EDITION (PRENTICE - HALL)

4) MODERN MATERIALS SCIENCE
IRVING GRANET
1st EDITION - 1980 (RESTON)

5) STEEL CONSTRUCTION MANUAL
AMERICAN INSTITUTE OF STEEL CONSTUCTION INC.
8th EDITION

6) HANDBOOK OF MATHMATICAL, SCIENTIFIC, AND ENGINEERING FORMULAS, TABLES, FUNCTIONS, GRAPHS, TRANSFORMS
RESEARCH AND EDUCATIONAL ASSOCIATION
1986

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SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

REFERENCES - CONT.

7) ORIGINAL DESIGN DRAWINGS
PRELOAD ENTERPRISES, INC.
5/T20 SERIES AND 5/T29 SERIES
ISSUED IN 1951

8) "K-65 SILOS STUDY AND EVALUATION FOR THE FEED MATERIALS PRODUCTION CENTER"
CAMARGO ASSOCIATES LIMITED
FEBRUARY 25, 1986

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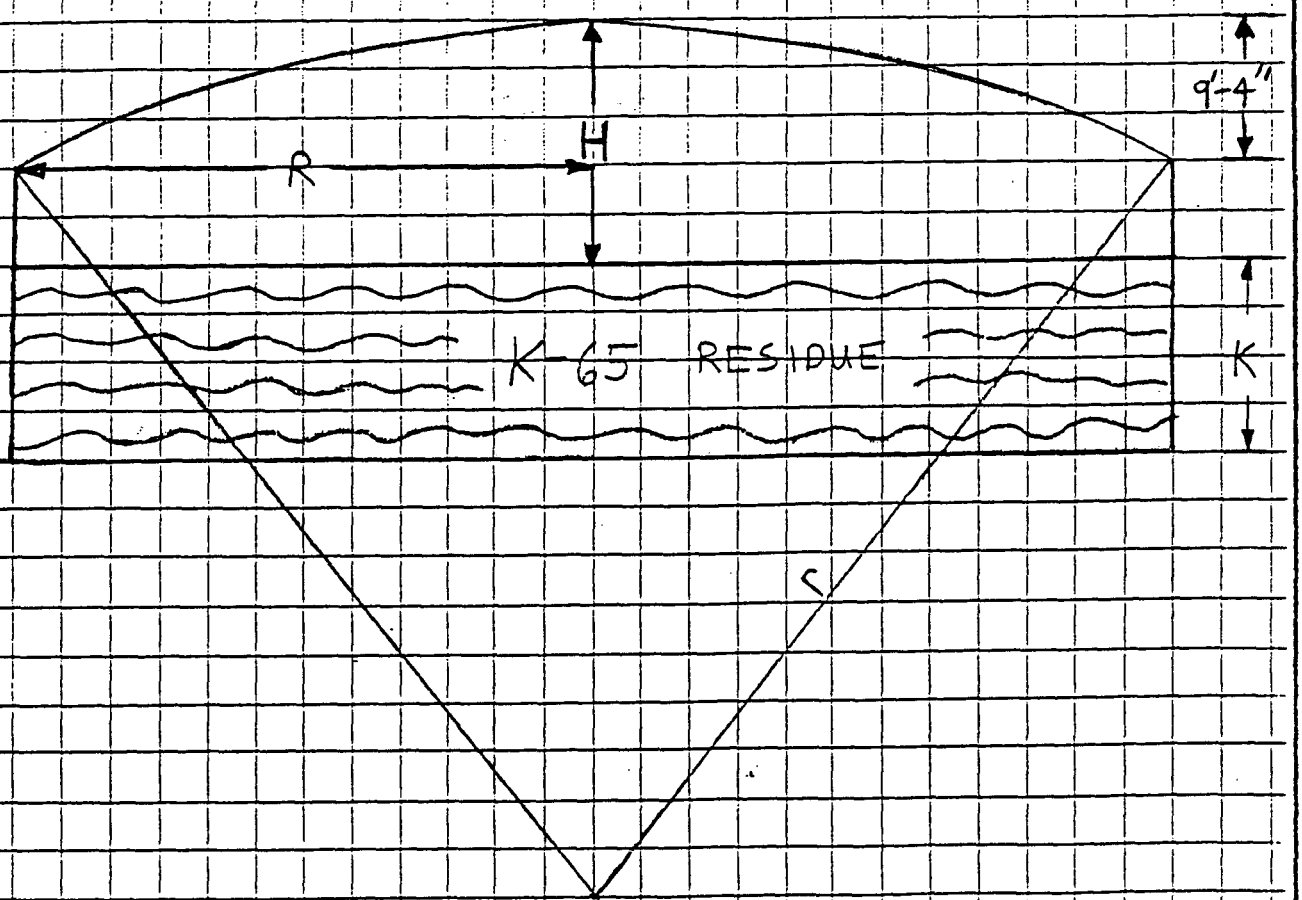
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



SKETCH OF DOME GEOMETRY

SILO #1	SILO #2
R = 40'	R = 40'
H = 15'-7"	H = 13'-7"
K = 20'	K = 22'

$b = 9'-4" = 112"$

$c = 2R = 80' = 960"$

$r = (4b^2 + c^2)/8b$

$r = (4(112)^2 + (960)^2)/8(112)$

$r \cong 1,084.6"$

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

DOME WEIGHT

ASSUMPTION - THE FOAM MUST SUPPORT THE ENTIRE WEIGHT OF THE DOME (EXCLUDING THE OUTER 2').

	DOME SECTION	THICKNESS	VOLUME $\pi(R^2-r^2)h$ (REF. #1 P. 2-13)
20'Ø CENTER	4'Ø	2"	$\pi(2)^2(\frac{2}{12}) = 2.09\ ft^3$
	4'Ø to 18.16'Ø	2½"	$\pi((9.08)^2-(2)^2)(\frac{2.5}{12}) = 51.34\ ft^3$
	18.16Ø to 20'Ø	3"	$\pi((10)^2-(9.08)^2)(\frac{3}{12}) = 13.79\ ft^3$
	20'Ø to 33.16'Ø	3"	$\pi((16.58)^2-(10)^2)(\frac{3}{12}) = 137.36\ ft^3$
	33.16Ø to 41.34'Ø	3½"	$\pi((20.67)^2-(16.58)^2)(\frac{3.5}{12}) = 139.60\ ft^3$
	41.34Ø to 56'Ø	4"	$\pi((28)^2-(20.67)^2)(\frac{4}{12}) = 373.59\ ft^3$
	56'Ø to 64'Ø	4½"	$\pi((32)^2-(28)^2)(\frac{4.5}{12}) = 282.74\ ft^3$
	64'Ø to 76'Ø	5"	$\pi((38)^2-(32)^2)(\frac{5}{12}) = 549.78\ ft^3$

TOTAL VOLUME = 1,550.29 ft^3

TOTAL WEIGHT (@ 150 pcf) = 1,550.29 × 150 = 232,544 lbs

VOLUME OF 20'Ø CENTER = 2.09 + 51.34 + 13.79 = 67.22 ft^3

WEIGHT OF 20'Ø CENTER = 67.22 × 150 = 10,083 lbs

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 3 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

DOME - LIVE LOAD

ASSUMPTION + 20 psf LIVE LOAD (PRIMARILY SNOW) AS STATED IN THE CAMARGO REPORT (REF #8 P. 27)

SURFACE AREA OF THE DOME = $2\pi rh$ (REF. #6 P. 145)

$r = 1{,}084.5'' = 90.38'$

$h = 9'\text{-}4'' + 2'' = 9'\text{-}6'' = 114''$

$A = 2\pi(90.38)(9.5) = 5{,}395\ ft^2$

LIVE LOAD = 20 psf × 5,395 ft^2 = **107,900 lbs**

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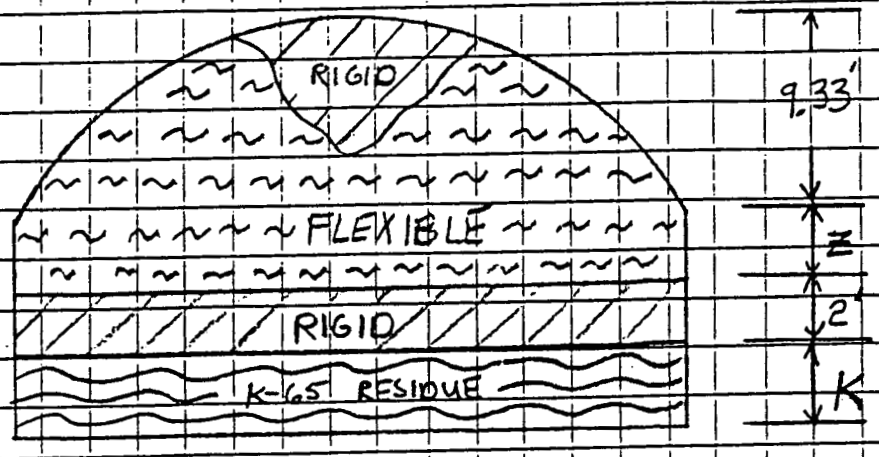
CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 4 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



SKETCH OF FOAM GEOMETRY

SILO #1	SILO #2
K = 20'	K = 22'
Z = 3'	Z = 1'

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 5 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

FOAM VOLUME

SILO #1

$V_{RIGID} = \pi(40)^2(2)$ (REF #1 P.2-12)

$V_{RIGID} = 10{,}053\ FT^3$

(REF #6 P.145) $V^*_{FLEX} = \pi(40)^2(z) + \frac{1}{3}\pi(9\frac{1}{3})^2(3(R)+9\frac{1}{3})$

WHERE $R = 90.38'$; $z = 3'$

$V_{FLEX} = \pi(40)^2(3) + \frac{1}{3}\pi(9\frac{1}{3})^2(3(90.38)-9\frac{1}{3})$

$V_{FLEX} = 15{,}080 + 23{,}883$

$V_{FLEX} = 38{,}963\ FT^3$

SILO #2

$V_{RIGID} = \pi(40)^2(2)$

$V_{RIGID} = 10{,}053\ FT^3$

$V_{FLEX} = \pi(40)^2(z) + \frac{1}{3}\pi(9\frac{1}{3})(3(R)-9\frac{1}{3})$

WHERE $R = 90.38'$; $z = 1'$

$V_{FLEX} = \pi(40)^2(1) + \frac{1}{3}\pi(9\frac{1}{3})(3(90.38)-9\frac{1}{3})$

$V_{FLEX} = 5{,}027 + 23{,}883$

$V_{FLEX} = 28{,}910\ FT^3$

THIS CALCULATION ASSUMES ALL FLEXIBLE FOAM ABOVE A 2' LAYER OF RIGID. THIS IS CONSERVATIVE FOR WEIGHT CALCULATIONS BECAUSE FLEXIBLE FOAM WEIGHS 5 pcf COMPARED TO 2 pcf FOR THE RIGID.

* V_{FLEX} IS THE VOLUME OF THE FLEXIBLE FOAM PLUS THE VOLUME OF RIGID UNDER THE CENTER OF THE DOME.

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR Jamie Campbell DATE 8-12-87 SHEET 6 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

FOAM WEIGHT

WORST CASE (SILO #1)

$V_{RIGID} = 10{,}053\ FT^3$
$\rho_{RIGID} = 2\ pcf$
$W_{RIGID} = (10{,}053) \times (2) = 20{,}106\ LBS.$

$V_{FLEX} = 38{,}963\ FT^3$
$\rho_{FLEX} = 5\ pcf$
$W_{RIGID} = (38{,}963) \times (5) = 194{,}815\ LBS.$

TOTAL FOAM WEIGHT = 20,106 + 194,815

TOTAL FOAM WEIGHT = 214,921 LBS. $\boxed{\sim 215{,}000\ LBS.}$

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 7 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

TOTAL WEIGHT

DOME WEIGHT = 232,544 lbs

DOME LIVE LOAD = 107,900 lbs

FOAM WEIGHT = 215,000 lbs

TOTAL WEIGHT = 555,444 lbs $\boxed{\sim 555{,}000 \text{ lbs}}$

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CALCULATION WORKSHEET

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

VERTICAL WALL

K-65 RESIDUE WEIGHT $= \pi(40)^2(20) \times 100$ pcf
$= 10{,}053{,}096$ lbs. (SILO #1)

DOME WEIGHT (DL + LL) = 340,444 lbs

FOAM WEIGHT = 215,000 lbs

THE HOOP STRESS INCREASES FROM 1,200 PSI COMP. TO 515 PSI COMP. WHEN THE CONTENTS ARE ADDED TO THE SILO ($\therefore \Delta\sigma_1 = 1200 - 515 = 685$ PSI) (REF. #8 P. 33)

$$\therefore \frac{\text{WEIGHT OF K-65 RESIDUE}}{\Delta\sigma_1} = \frac{\text{WEIGHT OF DOME + FOAM}}{\Delta\sigma_2}$$

WHERE $\Delta\sigma_2$ IS THE CHANGE IN HOOP STRESS DUE TO ADDING THE WEIGHT OF THE FOAM AND THE DOME (DL+LL) TO THE K-65 RESIDUE.

WEIGHT OF THE FOAM AND THE DOME $\cong$ 555,000 lbs

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ORIGINATOR James Campbell DATE 8-12-87 SHEET 9 OF 42
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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

VERTICAL WALL - CONT.

$\therefore \Delta\sigma_2 = \Delta\sigma_1$ (WEIGHT OF DOME + FOAM) / (WEIGHT OF RESIDUE)

$\Delta\sigma_2 = 685\,(555{,}000) / (10{,}053{,}096)$

$\Delta\sigma_2 = 37.8$ PSI

$\therefore \sigma_{HOOP} = 1200 - 685 - 37.8$

$\sigma_{HOOP} = 477.2$ PSI COMP.

THIS IS BASED ON A WORST CASE ASSUMING THAT 76'Ø PORTION OF THE DOME COLAPSES ON THE FOAM. EVEN IN THIS WORST CASE, THE VERTICAL WALL IS STILL IN COMPRESSION. SINCE THE WALL IS IN COMPRESSION, THE WALL IS STABLE.

NOTE: THIS CALCULATION WAS MADE ASSUMING MOSTLY RIGID FOAM WAS APPLIED UNDER THE DOME. A DESIGN CHANGE WAS MADE IN WHICH RIGID FOAM WOULD BE APPLIED ONLY UNDER THE CENTER 30'Ø PORTION OF THE DOME. THEREFORE, SUPPORT WILL BE PROVIDED ONLY FOR THAT PORTION. THUS THE ABOVE CALCULATION IS CONSERVATIVE.

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 10 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

BASE SLAB & EARTH BERM

A 2% INCREASE IN TOTAL CONTENT WEIGHT IS REALIZED DUE TO THE FOAM ADDITION. THEREFORE, NEITHER THE EARTH BERM NOR THE FOUNDATION WILL BE ADVERSELY EFFECTED BY THE ADDITION OF FOAM.

K-65 RESIDUE

THE FOAM SHOULD HAVE NO ADVERSE STRUCTURAL EFFECT ON THE K-65 RESIDUE PROVIDED THAT THE FOAM IS APPLIED UNIFORMLY DURING INSTALLATION.

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 11 OF 42
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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

ASSUMPTIONS :

1. THE DIMENSIONS ON THE K-65 SILO DRAWING (REF.#7) (PRELOAD DWG. # 517.20-3) ARE ACCURATE AT 110°F. THEREFORE, "b_4" = 9'-4".
2. THE CONNECTION OF THE DOME TO THE WALL IS A FIXED CONNECTION.
3. THE DOME CAN BE APPROXIMATED AS A SPHERICAL SEGMENT.

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 12 OF 42

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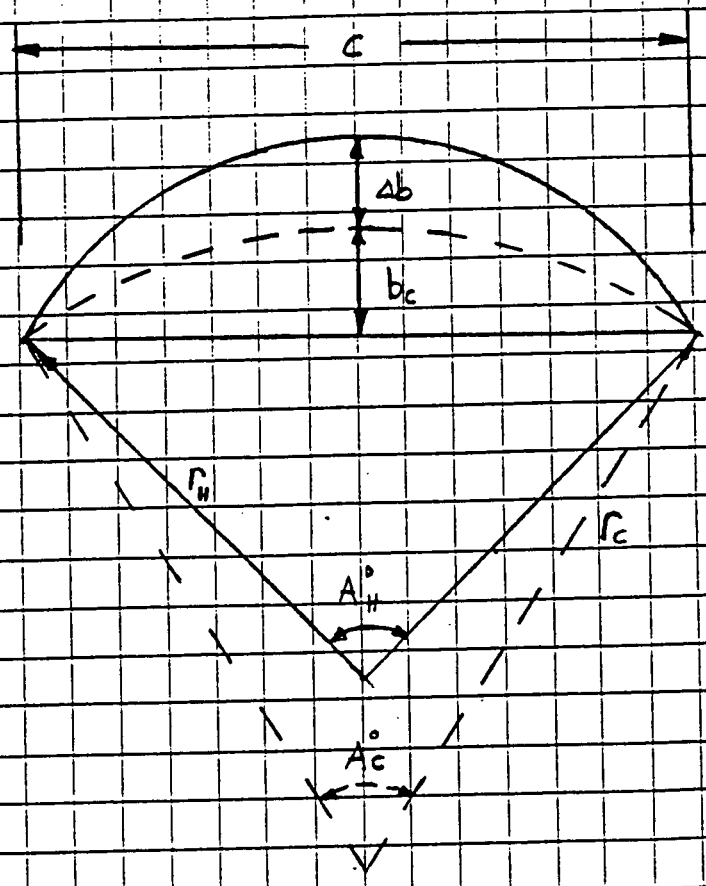
PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



GEOMETRY OF DOME EXPANSION / CONTRACTION

$b_H = b_c + \Delta b$

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CALCULATION WORKSHEET

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

DEFINITION OF TERMS:

A° = THE ANGLE DEFINING A SPHERICAL SEGMENT (DEGREE)
A_H° = "A°" @ 120°F
A_C° = "A°" @ -20°F
a = ARC ON THE SPHERE (IN.)
a_H = "a" @ 120°F
a_C = "a" @ -20°F
b = RISE FROM THE TOP OF THE SILO WALL TO THE INSIDE SURFACE AT THE DOME APEX. (IN.)
b_H = "b" @ 120°F
b_C = "b" @ -20°F
Δb = CHANGE IN "b" DUE TO THERMAL CONTRACTION (IN)
HYP. = HYPOTENUSE OF AN INSCRIBED TRIANGLE (DEGREE)
r = RADIUS OF A THEORETICAL SPHERE. (IN.)
r_H = "r" @ 120°F
r_C = "r" @ -20°F
θ = ANGLE IN AN INSCRIBED TRIANGLE (DEGREE)
ε_c = COEFFICIENT OF LINEAR THERMAL EXPANSION FOR CONCRETE
C = SILO DIAMETER = 80 FT.

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 14 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

VERTICAL DOME MOVEMENT

$C = 960''$

$r_H = (4(b_H)^2 + c^2) / 8(b_H)$ (REF. #5 P.6-18)

$r_H = (4(112)^2 + (960)^2) / 8(112)$

$r_H = 1{,}084.5'' = 90.38'$

$C = 2(r_H) \sin(A_H^\circ/2)$ (REF. #5 P.6-18)

$\therefore \sin(A_H^\circ/2) = c/(2(r_H))$

$(A_H^\circ/2) = \sin^{-1}(c/(2(r_H)))$

$(A_H^\circ/2) = \sin^{-1}(960/(2)(1{,}084.5))$

$(A_H^\circ/2) = 26.268045$

$A_H^\circ = 52.536091^\circ$

$a_H = (\pi r_H A_H^\circ / 180^\circ)$ (REF. #5 P6-18)

$a_H = \pi(1{,}084.5)(52.536091)/180$

$a_H = 994.47363''$

$\varepsilon_c = 5.5 \times 10^{-6}$ in/in°F

$\Delta T = T_H - T_C = 120°F - (-20°F) = 140°F$

$\Delta a = a_H - a_C$

$a_C = a_H - (a_H)(\varepsilon_c)(\Delta T)$ (REF. #4 P.17)

$a_C = 994.47363 - (994.47363)(5.5 \times 10^{-6})(140)$

$a_C = 993.70789''$

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 15 OF 42
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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

AFTER CONTRACTION:

$a_c = 993.70789''$
$c = 960''$

$a_c = \pi (r_c)(A^\circ_c) / 180$ (REF. #5 P. 6-18)
$993.70789 = \pi (r_c)(A^\circ_c) / 180$

$(r_c)(A^\circ_c) = 56{,}935.268$ (EQ. #1)

$c = 2(r_c) \sin (A^\circ_c / 2)$ (REF. #5 P. 6-18)
$960 = 2(r_c) \sin (A^\circ_c / 2)$

$(r_c) \sin (A^\circ_c / 2) = 480$ (EQ. #2)

SOLVING EQ. #1 AND EQ. #2 SIMULTANEOUSLY

$r_c = 1{,}095.6795''$

$A^\circ_c = 51.963433^\circ$

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 16 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

(REF. #5 P. 6-18)

$b_c = (c/2)\,TAN\,(A_H^\circ/4)$

$b_c = (960/2)\,TAN\,(51.963433/4)$

$b_c = 480\,TAN\,(12.990858)$

$b_c = 110.73607''$

$\Delta b = b_H - b_c$

$\Delta b = 112'' - 110.73607''$

$\Delta b = 1.2639336''$

∴ THE MAXIMUM MOVEMENT OF THE UNINSULATED DOME IS ~ 1.264" (FROM -120°F TO 120°F)

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ORIGINATOR James Campbell DATE 8-12-87 SHEET 17 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

EXPOSED CONCRETE TEMP. - SUMMER

$q_r = \sigma A \varepsilon_1 (T_1^4 - T_2^4)$ (REF. #2 P. 12)

σ = Stefan - Boltzman constant = 0.1713×10^{-8} BTU/HR FT^2 °F
A = Area (ft^2) (assume 1 ft^2 for this calculation)
ε_1 = EMISSIVITY = 0.9
T_1 = CONCRETE TEMP (°R)
T_2 = AMBIENT TEMP. (°R)
q_r = SOLAR RADIATION INCIDENT UPON A HORIZONAL SURFACE

$q_r = (0.1713 \times 10^{-8})(1)(0.9)(T_1^4 - (120+460)^4)$

$q_r = 300$ BTU/HR FT^2 $\times$ 1 FT^2 = 300 BTU/HR (REF. #3 P. 341)
$\therefore T_1 = 745°R = 285°F$
$q_{convection} = h_o A \Delta t$ (REF. #2 P. 13)

h_o = SURFACE HEAT TRANSFER COEFFICIENT = 1.63 BTU/HR FT^2 °F
A = 1 ft^2
Δt = AVERAGE SURFACE TEMPERATURE - T_2
$q_{conv.} = (1.63)(1)(\frac{285+120}{2} - 120) \cong 135$ BTU/HR
$q_R = q_r - q_{conv} = 165$ BTU/HR

$\therefore 165 = (0.1713 \times 10^{-8})(1)(0.9)(T_1^4 - (580)^4)$

$T_1^* \cong 685°R \cong 225°F$

* THIS IS A SIMPLIFIED ESTIMATE OF CONCRETE TEMPERATURE. THE PURPOSE OF THIS CALCULATION IS TO SHOW THAT EXPOSED CONCRETE WILL EXCEED AMBIENT AIR TEMPERATURE (NOT TO PREDICT THE ACTUAL TEMP.)

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 18 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

INSULATING THE DOME

THE TEMPERATURE OF UNINSULATED CONCRETE WILL EXCEED AMBIENT AIR TEMPERATURE DUE TO SOLAR RADIATION. THIS WILL PRODUCE A THERMAL CYCLIC STRESS ON THE DOME EVERY 24 HOURS AND ALMOST DOUBLE THE AMOUNT OF RISE ("b") IN THE DOME CALCULATED IN PREVIOUS CALCULATIONS

ADVANTAGES TO INSULATING THE DOME

1. TO ELIMINATE TO SOLAR LOAD ON THE CONCRETE AND REDUCE "ΔT" IN THE CONCRETE.

2. REDUCE "ΔT" IN THE SUPPORTING FOAM.

3. WEATHER PROOF TO REDUCE DEGRADATION.

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ORIGINATOR James Campbell DATE 8-12-87 SHEET 19 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

ASSUMPTIONS :

1. HEAT TRANSFER IS SIMPLIFIED TO CONDUCTANCE ONLY, BY ASSUMING THE RADIATION LOAD ON THE INSULATION IS EQUAL TO THE CONVECTION OFF OF THE INSULATION, THEREFORE, THE INSULATION SURFACE TEMPERATURE (T_o) IS EQUAL TO THE AMBIENT AIR TEMPERATURE (T_∞).

2. ALL FOAM BELOW GROUND LEVEL = GROUND TEMP.

3. THE CONCRETE TEMPERATURE AT THE DOME - SIDE WALL CONNECTION IS = GROUND TEMP.

4. NO ALLOWANCE IS MADE FOR THE INCREASE IN CONDUCTIVITY THAT THE STEEL ADDS TO THE CONCRETE.

5. NO ALLOWANCE IS MADE FOR VARIATION IN CONCRETE THICKNESS.

6. THE DOME TEMPERATURE CLOSE TO THE SIDEWALL IS NOT USED IN DETERMINING THE AVERAGE DOME TEMPERATURE.

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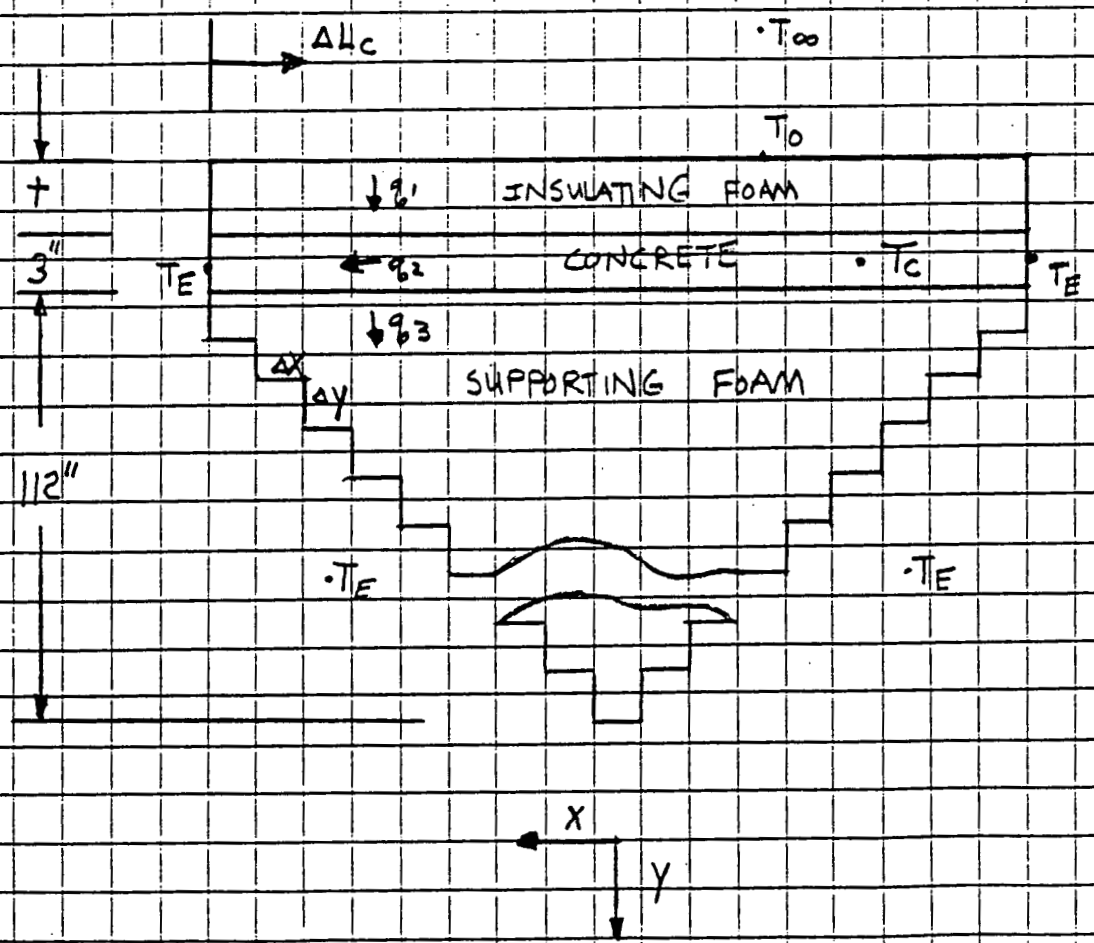
CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 20 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



HEAT TRANSFER SKETCH

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 21 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

DEFINITION OF TERMS:

Δy = VERTICAL INCREMENT (IN.)
Δx = HORIZONAL INCREMENT (IN.)
q_c = CONDUCTION HEAT TRANSFER
q_1 = CONDUCTION THROUGH THE DOME INSULATION
q_2 = CONDUCTION THROUGH CONCRETE TO SIDEWALLS
q_3 = CONDUCTION THROUGH THE SUPPORT FOAM
A_{F1} = AREA FACTOR FOR "q_1"
A_{F2} = AREA FACTOR FOR "q_2"
A_{F3} = AREA FACTOR FOR "q_3"
C_{F1} = CONDUCTION FACTOR FOR "q_1"
C_{F2} = CONDUCTION FACTOR FOR "q_2"
C_{F3} = CONDUCTION FACTOR FOR "q_3"
ΔL_c = RADIAL DISTANCE FROM SIDEWALL INWARD (IN.)
t = THICKNESS OF FOAM INSULATION (IN.)
T_∞ = AMBIENT TEMPERATURE (°F) = 120°F
T_E = EARTH TEMPERATURE (°F) = 50°F
T_o = SURFACE TEMPERATURE (°F) = 120°F
T_c = CONCRETE TEMPERATURE (°F)

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 22 OF 42

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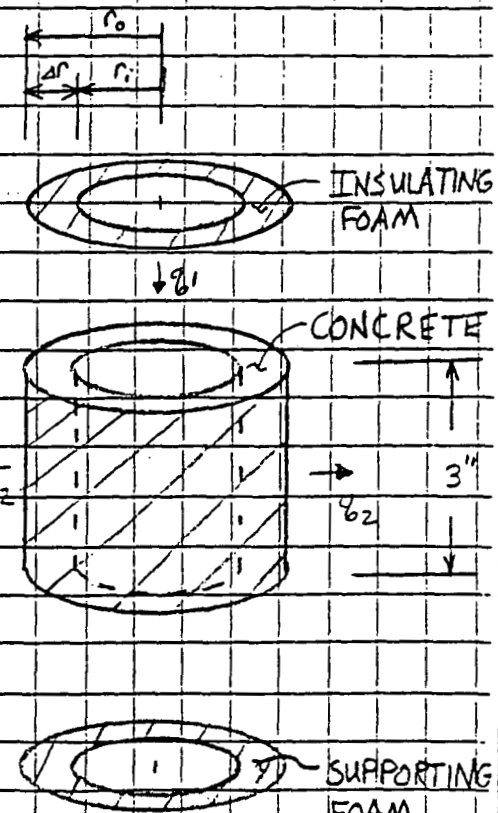
PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

AREA FACTOR * (A_F)



A_1 = AREA $\perp$ TO q_1 (INSULATING FOAM)

$A_1 = \pi((r_o)^2 - (r_i)^2)$ (REF. #5 P. 6-22)

A_2 = AREA $\perp$ TO q_2 (CONCRETE)

$A_2 = \pi\left(\frac{2(r_o) + 2(r_i)}{2}\right)(3'')$

A_3 = AREA $\perp$ TO q_3 (SUPPORTING FOAM)

$A_3 = \pi((r_o)^2 - (r_i)^2)$

$\therefore A_1 = A_3$

$A_1/A_2 = \pi((r_o)^2 - (r_i)^2) / \pi(r_o + r_i)(3)$

IF $r_o = 240''$ THEN $r_i = 240 - \Delta x = 235.7143''$

$A_1/A_2 = \pi((240)^2 - (235.7143)^2) / \pi(240 + 235.7143)(3)$

$A_1/A_2 = 1.44$

$A_{F1} = A_1/A_2 = 1.44$; $A_{F2} = A_2/A_2 = 1$; $A_{F3} = A_3/A_2 = A_1/A_2 = 1.44$

* THE AREA FACTOR GIVES A RATIO OF EACH CONDUCTANCE AREA RELATED TO THE CONCRETE AREA (SURFACE AREA OF A HOLLOW CYLINDER). IT IS PROVIDED SO THAT THE AREA OF EVERY SEGMENT IN THE DOME DOES NOT NEED TO BE CALCULATED. INSTEAD, THE AREA FACTOR (RATIO OF AREAS) CAN BE USED FOR EVERY SEGMENT AS IT IS CONSTANT.

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 23 OF 42
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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

CONDUCTANCE FACTOR (CF)

SINCE $q_c = A\left(\frac{k}{x}\right)(\Delta T)^*$, q_c VARIES DIRECTLY WITH AREA, THERMAL CONDUCTIVITY, AND TEMPERATURE AND INDIRECTLY WITH THICKNESS.

A CONDUCTANCE FACTOR (CF) CAN BE OBTAINED FOR EACH OF THE THREE CONDUCTIVE HEAT TRANSFER MEDIUMS BY SETTING $CF = (A_F)(T_i)(K)/t$. WHERE "t" IS THE THICKNESS OF EACH MEDIUM AT EACH GIVEN SEGMENT.

FOR INSULATING FOAM: t = INSULATION THICKNESS (t)

FOR CONCRETE: t = RADIAL DISTANCE FROM EACH GIVEN SEGMENT TO THE SIDEWALL (ΔL_c)

FOR SUPPORTING FOAM: t = VERTICAL DISTANCE FROM THE INSIDE SURFACE OF THE DOME TO GROUND LEVEL (RESIDUE) (Δy)

* REF. #3 P. 22

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 24 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

CONDUCTANCE FACTOR - CONT.

$\therefore C_{F1} = (A_{F1})(T_o)(K_1) / t$

$C_{F1} = (1.44)(120)(0.15) / t$

$C_{F1} = 25.92 / t$

$C_{F2} = (A_{F2})(T_E)(K_2) / \Delta L_c$

$C_{F2} = (1)(50)(12.0) / \Delta L_c$

$C_{F2} = 600 / \Delta L_c$

$C_{F3} = (A_{F3})(T_E)(K_3) / \Delta y$

$C_{F3} = (1.44)(50)(0.15) / \Delta y$

$C_{F3} = 10.8 / \Delta y$

$\therefore T_c = ((C_{F1} * T_o) + ((C_{F3} + C_{F2}) \times T_E)) / (C_{F1} + C_{F2} + C_{F3})$

THE FOLLOWING TABLE SHOWS T_c AT VARIOUS INSULATION THICKNESSES (t).

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 25 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

T_c (CONCRETE TEMPERATURE)

		+ (INSULATION THICKNESS)					
		2"	4"	6"	12"	24"	36"
ΔL_c	Δy	T_c(°F)	T_c(°F)	T_c(°F)	T_c(°F)	T_c(°F)	T_c(°F)
48"	11.2"	83.4	72.7	67.0	59.7	55.2	53.6
96"	22.4"	96.1	84.3	77.4	67.0	59.7	56.8
144"	33.6"	102.0	91.4	84.3	72.7	63.6	59.7
192"	44.8"	105.6	96.1	89.3	77.4	67.0	62.3
240"	56.0"	108.0	99.5	93.1	81.2	70.0	64.8
288"	67.2"	109.7	102.0	96.1	84.3	72.7	67.0
336"	78.4"	111.0	104.0	98.4	87.0	75.2	69.1
384"	89.6"	112.0	105.6	100.4	89.3	77.4	71.0
432"	100.8"	112.8	106.9	102.0	91.4	79.3	72.7
480"	112.0"	113.4	108.0	103.4	93.1	81.2	74.4

ADVANCED SCIENCES, INC.

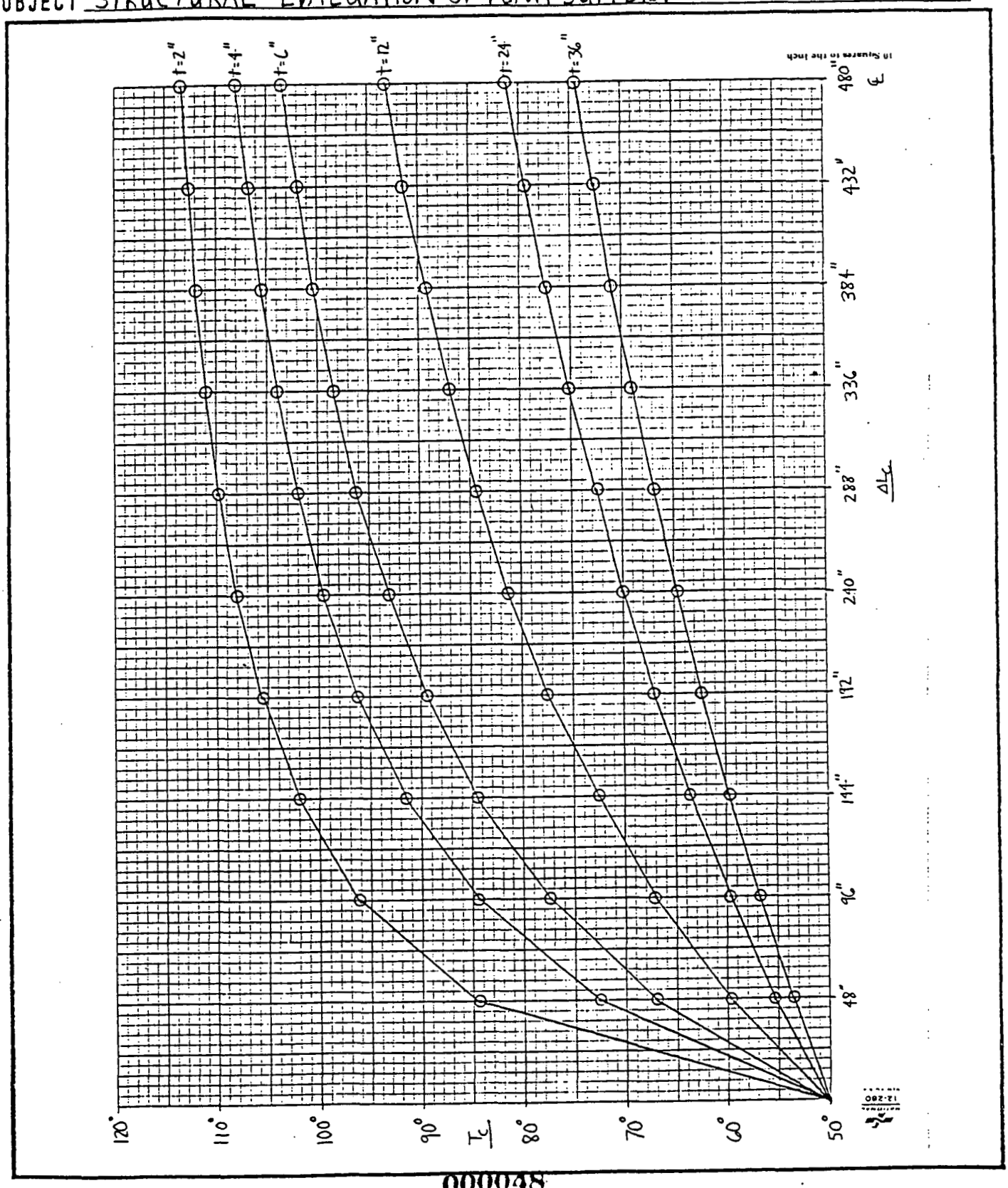
CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 26 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



RANGED SCIENCES, INC.

ORIGINATOR James Campbell DATE 8-12-87 SHEET 27 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

AVERAGE DOME TEMPERATURES

W/ 2" OF INSULATION:

$T_c = (84.3 + 96.1 + 102.0 + 105.6 + 108.0 + 109.7 + 111.0 + 112.0 + 112.8 + (113.4)(1/2)) / (9\frac{1}{2})$

$T_c = 105.1°F$

SIMILARLY:

W/ 4" OF INSULATION $\Rightarrow T_c = 96.4°F$

W/ 6" OF INSULATION $\Rightarrow T_c = 90.5°F$

W/ 12" OF INSULATION $\Rightarrow T_c = 79.5°F$

W/ 24" OF INSULATION $\Rightarrow T_c = 69.5°F$

W/ 36" OF INSULATION $\Rightarrow T_c = 64.7°F$

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 28 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

MAXIMUM INSULATED DOME MOVEMENT

ASSUMING THAT THE RELATIONSHIP BETWEEN THE TEMPERATURE CHANGE (ΔT) AND THE VERTICAL DOME MOVEMENT (Δb) IS LINEAR, THE FOLLOWING VALUES ARE OBTAINED:

$$\Delta T = 140 - [(120 - T_c) \times 2]$$

AMOUNT OF INSULATION (+)	ΔT	VERTICAL MOVEMENT (Δb)
PREVIOUS CALC. 0"	120 - (-20) = 140°F	1.26"
2"	105.1 - (-5.1) = 110.2°F	0.99"
4"	96.4 + 3.6 = 92.8°F	0.84"
6"	90.5 + 9.5 = 81.0°F	0.73"
12"	79.5 - 20.5 = 59.0°F	0.53"
24"	69.5 - 30.5 = 39.0°F	0.35"
36"	64.7 - 35.3 = 29.4°F	0.26"

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 29 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

ASSUMPTION: ALL FOAM AT, AND BELOW GROUND LEVEL REMAINS AT A CONSTANT TEMPERATURE (EARTH TEMPERATURE).

∴ MAXIMUM DEPTH OF RIGID FOAM THAT WILL BE SUCEPTIBLE TO THERMAL EXPANSION/CONTRACTION IS 9⅓' (112").

W/2" OF INSULATION ⇒ MAXIMUM DOME TEMP. = 105.1°F
W/4" OF INSULATION ⇒ MAXIMUM DOME TEMP. = 96.4°F
W/6" OF INSULATION ⇒ MAXIMUM DOME TEMP. = 90.5°F

IF THE AVERAGE RIGID FOAM TEMPERATURE IS EQUAL TO THE AVERAGE OF THE DOME AND EARTH TEMPERATURE, THEN:

FOAM TEMP. W/2" INSULATION = (105.1 + 50)/2 = 77.55°F
ΔT = 77.55°F - 50°F = 27.55°F

FOAM TEMP. W/4" INSULATION = (96.4 + 50)/2 = 73.2°F
ΔT = 73.2 - 50 = 23.2°F

FOAM TEMP. W/6" INSULATION = (90.5 + 50)/2 = 70.25°F
ΔT = 70.25 - 50 = 20.25°F

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 30 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

∴ MAXIMUM LINEAR EXPANSION OF THE RIGID FOAM $= (\alpha)(L)(\Delta T)$*

WHERE : α = COEF. OF LINEAR EXPANSION $= 3.5 \times 10^{-5}$ in/in °F

$L = 9\frac{1}{3}'$ (112")

ΔT = TEMPERATURE CHANGE (°F)

W/2" INSULATION : $(3.5 \times 10^{-5})(112)(27.55) = 0.108"$

W/4" INSULATION : $(3.5 \times 10^{-5})(112)(23.2) = 0.091"$

W/6" INSULATION : $(3.5 \times 10^{-5})(112)(20.25) = 0.079"$

W/12" INSULATION : $(3.5 \times 10^{-5})(112)(14.75) = 0.058"$

W/24" INSULATION : $(3.5 \times 10^{-5})(112)(9.75) = 0.038"$

W 36" INSULATION : $(3.5 \times 10^{-5})(112)(7.35) = 0.029"$

* REF. #4 P. 17

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 31 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

LOOKING AT THE EXPANSION / CONTRACTION CHARACTERISTICS OF THE CONCRETE DOME COMPARED TO THE RIGID SUPPORTING FOAM (SEE THE GRAPH ON PAGE 34), THE CONCRETE DOME EXHIBITS MUCH MORE MOVEMENT. THEREFORE, THE FORCE EXERTED ON THE CONCRETE BY THE FOAM WILL DECREASE IN THE SUMMER AND INCREASE IN THE WINTER. THE MAXIMUM ALLOWABLE FORCE MUST BE DETERMINED UNDER WINTER CONDITIONS.

IN DETERMINING THE MAXIMUM ALLOWABLE FORCE FOR THE CENTER PORTION OF THE DOME, THE MINIMUM THICKNESS OF FLEXIBLE FOAM DIRECTLY UNDERNEATH THE CENTER PORTION WILL BE DETERMINED.

(δ_{max}) MAX. DEFLECTION = CONTRACTION OF DOME − CONTRACTION OF FOAM

W/2" OF INSULATION: $\delta_{max} = \left(\frac{\Delta b}{2}\right) + 0.108 = \frac{0.99}{2} - 0.108 = 0.387''$

WORST CASE (FOAM INSTALLED UNDER SUMMER CONDITIONS)

$\delta_{max} = \Delta b - (2)(0.108) = 0.99 - (2)(.108) = \boxed{0.774''}$

NOTE: Δb IS BASED ON THE DOME MOVEMENT FROM −20°F TO 120°F. THE CONTRACTION OF THE FOAM IS BASED ON AN AMBIENT TEMPERATURE CHANGE OF 70°F. THEREFORE, THE FOAM CONTRACTION WOULD DOUBLE IF THE TEMPERATURE CHANGE WAS 140°F (120°F to −20°F).

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 32 OF 42

CALC.NO. 60295-01 REV.NO. 1 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

W/ 4" OF INSULATION:

WORST CASE: $\delta_{MAX} = \Delta b - (2)(.0911) = 0.84 - (2)(.091) = \boxed{0.658''}$

W/ 6" OF INSULATION:

WORST CASE: $\delta_{MAX} = \Delta b - (2)(0.074) = 0.73 - (2)(0.074) = \boxed{0.572''}$

NEGLECTING THE FORCE ABSORBED BY THE RIGID FOAM

$\delta = P\left(\frac{L}{E}\right)$ (REF #4 P. 12)

P = PRESSURE ON THE CENTER PORTION OF THE DOME (psi)

L = DEPTH OF FLEXIBLE FOAM

E = MODULUS OF ELASTICITY OF THE FLEXIBLE FOAM (psi) = 3.6 psi

"E" WAS OBTAINED FROM MFR. DATA (SEE PAGE 37), BY THE RELATIONSHIP

$1'' = (45^{\#}/50\,in^2)(4''/E)$ @ 25% DEFLECTION $\Rightarrow E = 3.6$ psi

IF $P = P_{MAX} = 26$ psf (CAMARGO REPORT PAGE 31)

THEN:

W/2" OF INSULATION: $\delta = 0.774''$

$\delta = P\left(\frac{L}{E}\right) = \left(\frac{26}{144}\right)\left(\frac{L}{3.6}\right)$

$0.774 = \left(\frac{26}{144}\right)\left(\frac{L}{3.6}\right)$

$\Rightarrow L \cong 16''$ (MINIMUM ALLOWABLE DEPTH OF FLEX FOAM)

NOTE: SUBSEQUENT CALCS USED A VALUE FOR COMPRESSIVE MODULUS OF FLEXIBLE FOAM OF .9 PSI, SEE PG 36 of 42 checked 9 [illegible] 8-14-88

1

NOTE: THE DEFLECTION - PRESSURE RELATIONSHIP ESTABLISHED FOR THE FLEXIBLE FOAM IS ASSUMED LINEAR BASED UPON A TELECON WITH THE FOAM MANUFACTURER (SEE PAGE 36)

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 33 OF 42.
CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED
PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

SIMILARLY:

W/ 4" OF INSULATION : $\delta = 0.658''$

$\delta = P\left(\frac{L}{E}\right)$ (REF. #4 P.12)

$0.658 = \left(\frac{26}{144}\right)\left(\frac{L}{26}\right)$

$\Rightarrow L \cong 13''$

W/ 6" OF INSULATION : $\delta = 0.572''$

$\delta = P\left(\frac{L}{E}\right)$ (REF #4 P.12)

$0.572 = \left(\frac{26}{144}\right)\left(\frac{L}{26}\right)$

$\Rightarrow L \cong 12''$

THEREFORE, THE MINIMUM THICKNESS OF FLEXIBLE FOAM RANGES FROM 12" TO 16". INCREASING THIS MINIMUM BY 100% (24" TO 32"), WHILE SLIGHTLY REDUCING THE SUPPORT THE FOAM GIVES TO THE DOME, WILL REDUCE THE CONCERN RELATING TO THE UNCERTAIN BEHAVIOR OF THE RIGID FOAM DURING THE EARLY STAGES OF CURING (~4 weeks).

ADVANCED SCIENCES, INC.

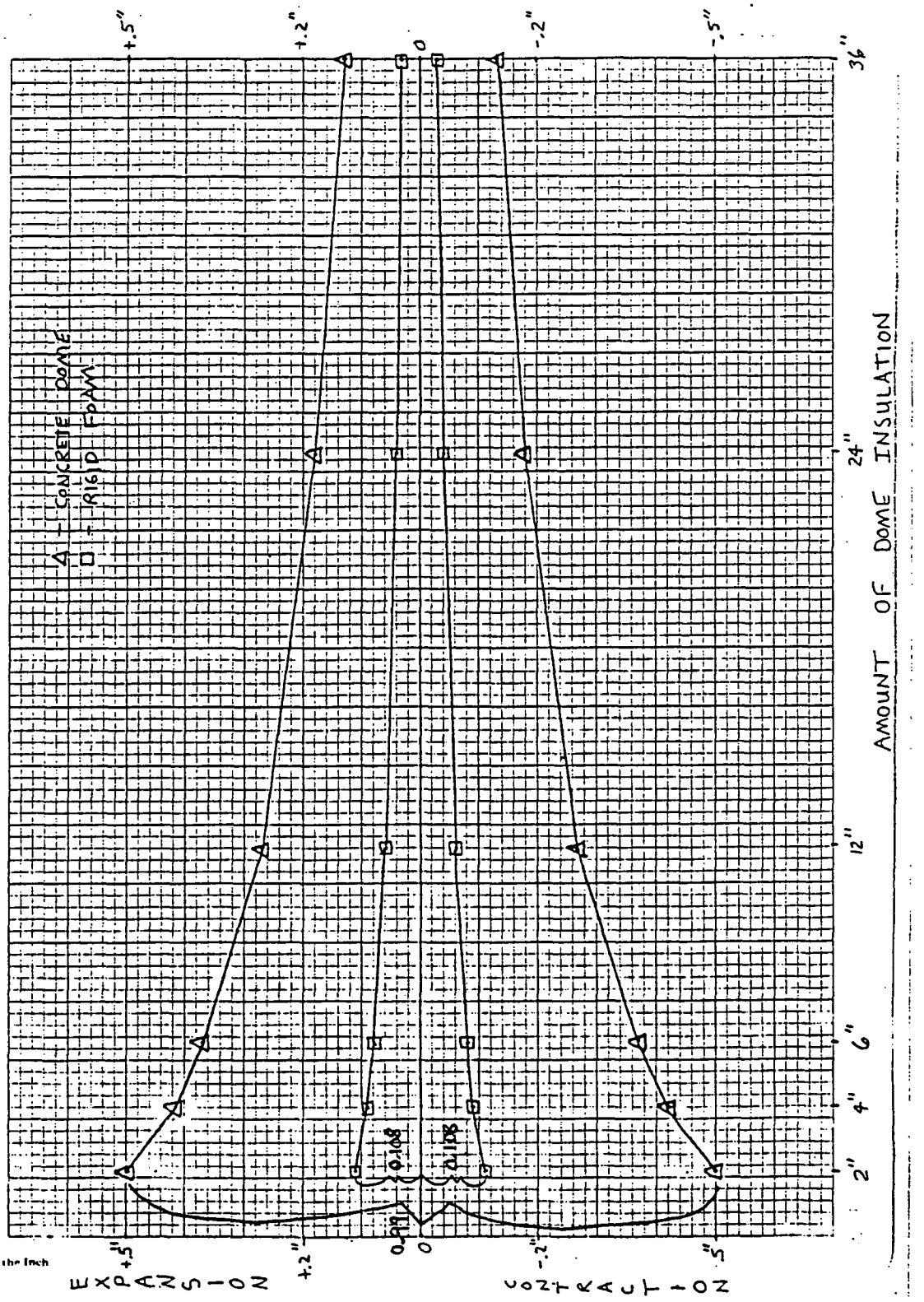
CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 34 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



ADVANCED SCIENCES, INC

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 35 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

SUPPORT FOAM DISCUSSION

THE COMPRESSION MODULUS OF THE RIGID FOAM IS 24 PSI. THEREFORE, THE RIGID FOAM CAN CARRY THE DEAD WEIGHT LOAD (DL) OF THE CENTER 20'Ø PORTION OF THE DOME PLUS THE 20 PSF LIVE LOAD (LL).

THUS, THE DESIGN CAN SUSTAIN THE WEIGHT OF THE CENTER 20'Ø PORTION OF THE DOME PLUS THE 20 PSF LIVE LOAD. HOWEVER, NO SUPPORT IS PROVIDED FOR THE REMAINING PORTION OF THE DOME.

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

5976

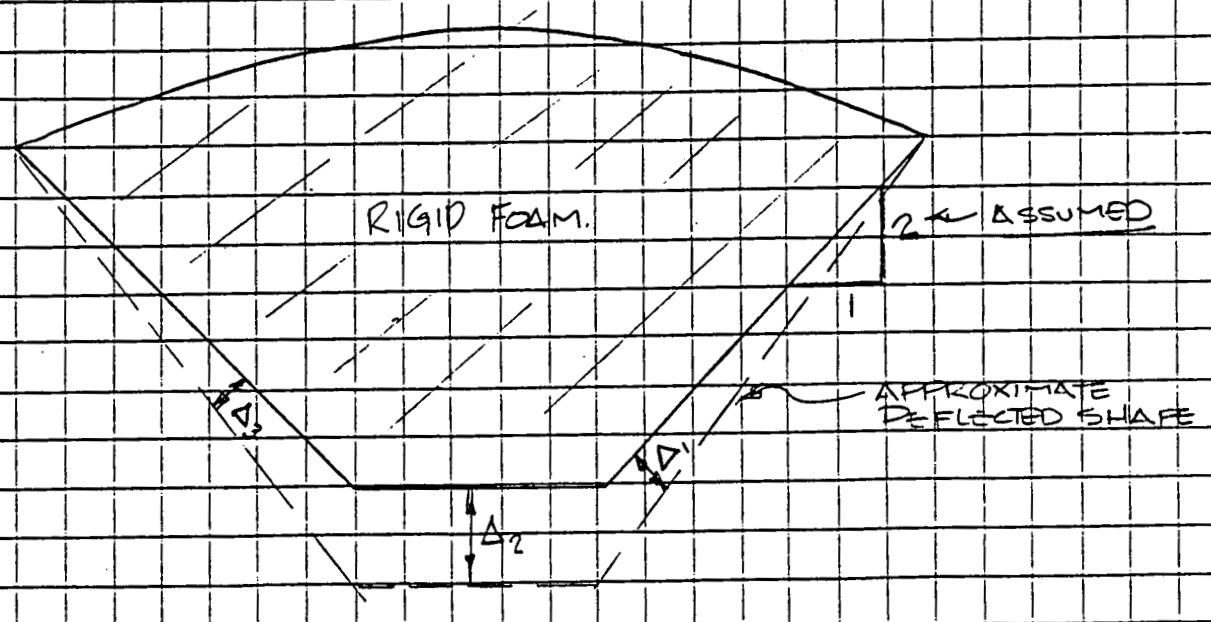
ORIGINATOR [signature] DATE 8-20-87 SHEET 56 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8/21/87 CHECKED [signature]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

THE PURPOSE OF THE FOLLOWING CALCULATION IS TO DEMONSTRATE A RELATIONSHIP BETWEEN % VOLUME CHANGE OF FOAM DURING CURING AND THE RESULTING DEFLECTION OF A FLEXIBLE FOAM LAYER OF A CERTAIN THICKNESS. THE LOAD APPLIED TO THE DOME IS A RESULT OF THIS DEFLECTION OF FLEXIBLE FOAM.



ASSUMPTIONS – • FLEXIBLE FOAM OBEYS HOOKE'S LAW

$E_{(FLEXIBLE\ FOAM)} = \frac{45^{\#}}{50 IN^2} = .9\ PSI = 129.6\ PSF$ (PG)

• 2:1 SLOPE.

HEIGHT OF CONTENTS = 20' (SILO WITH LARGEST VOID VOL (SILO #1))

TOTAL HEIGHT OF SILO FROM GROUND LEVEL TO DOME TOP

= 26'-8" + 9'-4" = 36'

36
− 20 – CONTENTS
− 2'-2" – LAYER OF RIGID FOAM.
11'-10" ≈ 12'-0" ← MAX HEIGHT FOR CALCULATING EXP.

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 8·20·97 SHEET 37 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8/21/97 CHECKED [illegible]

PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

THE RIGID FOAM IS MODELED AS CONCENTRIC VOLUMES. THE VOLUMETRIC INCREASE IS CALCULATED DUE TO FOAM EXPANSION. THE INCREASE IN HEIGHT (h) IS CALCULATED BY THE FOLLOWING RELATIONSHIPS.

EQN 1.- VOLUME FOR SOLID CYLINDER $V = \frac{\pi}{4} d^2 h$ d - DIAMETER OF CYLIN.

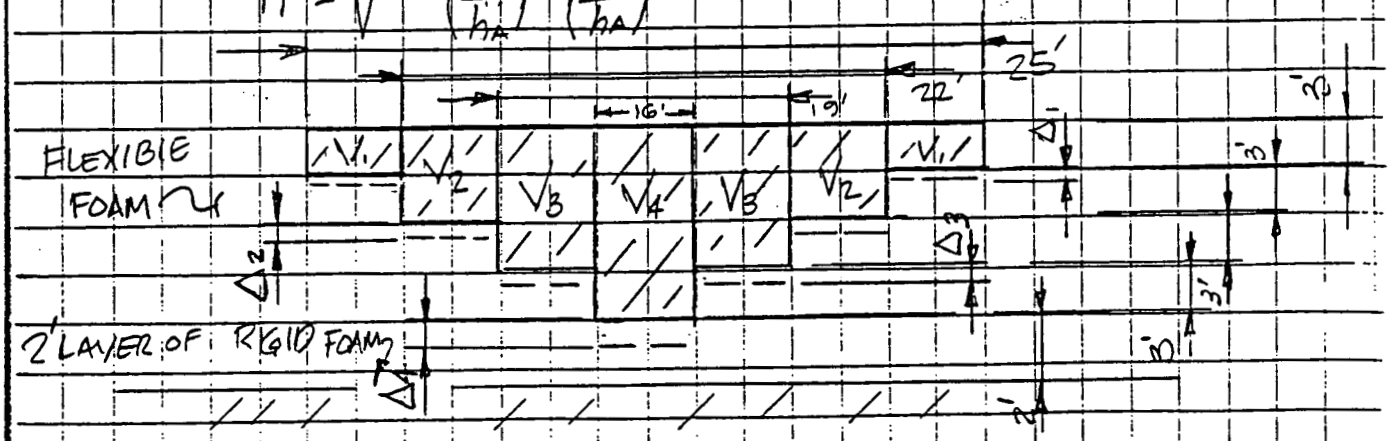
EQN 2.- VOLUME FOR HOLLOW CYLINDER $V = \frac{\pi}{4}(d_o^2 - d_i^2)h$ d_o - OUTSIDE DIA, d_i - INSIDE DIA.

USING THE RELATIONSHIP $d = \frac{d_A}{h_A} h$ SUBSTITUTE IT INTO EQN 1. h CAN BE SOLVED FOR WHEN SET EQUAL TO THE EXPANDED VOLUME (V_E). d_A = ORIGINAL DIAMETER h_A = ORIGINAL HEIGHT

$$V_E = \frac{\pi}{4}\left(\frac{d_A}{h_A} h\right)^2 h \Rightarrow h = \sqrt[3]{\frac{V_E\,(4)}{\pi\,(d_A/h_A)^2}} \quad \text{EQN (3)}$$

SIMILIARLY, FOR EQN 2.

$$h = \sqrt[3]{\frac{V_E\,(4)}{\pi\left(\frac{d_o}{h_A}\right)^2 - \left(\frac{d_i}{h_A}\right)^2}} \quad \text{EQN (4)}$$



CROSS SECTION VIEW OF RIGID FOAM MODEL

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 8-20-87 SHEET 38 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8/21/87 CHECKED [illegible]

PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

NEXT CALCULATE Δ

Δ = h (EXPANDED VOLUME) − h (ORIGINAL VOLUME)

$\frac{\Delta}{X}$ = % DEFLECTION OF THE FLEXIBLE FOAM.
WHERE X = THE DISTANCE FROM VOLUME ELEMENT TO THE LOWER RIGID FOAM LAYER (FT).

THE LOAD (PSF) IS CALCULATED FROM THE FOLLOWING RELATIONSHIP.

$\frac{\%\ DEFL.}{25\%} \times 129.6$ = LOAD (PSF) (EQN 5)

THE TOTAL LOAD (LBS) PRODUCED BY THE EXPANDED VOLUME ELEMENT = LOAD (PSF) × AREA (FT^2) = LOAD (LBS)

EXAMPLE: FOR VOLUME #1

$A = \pi/4\ (25^2 - 22^2) = 110.7\ ft^2$ $V = Ah = 110.7(3) = 332.2\ ft^3$

$V \times 1.06 = 352.2$ $h = \sqrt[3]{\frac{(352.16)(4)}{\pi\left[(25/3)^2 - (22/3)^2\right]}} = 3.058' \doteq 3.06'$

$\Delta = .06$ $X = 3(3) + 2 = 11'$ $\frac{\Delta}{X} = .0055$

LOAD (PSF) = $\frac{.0055}{.25}(129.6) = 2.85$ PSF

LOAD (lbs) = $110.7(2.85) = 315.6^{\#} \approx 316^{\#}$.

VALUES ARE TABULATED ON THE FOLLOWING PG.

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 8-20-87 SHEET 39 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8/21/87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

VOL. #	SURFACE AREA ($\pi/4\, d^2$) OR $\pi/4(d_o^2 - d_i^2)$ (ft^2)	VOLUME SUR. AREA x h. (ft^3)	VOLUME x 1.06 (ft^3)	NEW h (FT)	Δ (FT)	x (FT)	LOAD (PSF)	LOAD (lbs)
1	110.7	332.2 (h=3)	352.2	3.06	.06	11	2.85	516
2	96.6	579.6 (h=6)	614.4	6.12	.12	8	7.78	751.2
3	82.5	742.5 (h=9)	787.1	9.18	.18	5	18.66	1539.6
4	201.1	2413.2 (h=12)	2558	12.23	.23	2	59.6	11988.8
Σ	490.9	Σ 4067.3						Σ 14595.6

THE AVERAGE LOAD ON THE DOME IN lbs = 14595.6.
(DUE TO FOAM EXPANSION)

THE AVERAGE LOAD ON THE DOME IN PSF =
(DUE TO FOAM EXPANSION)

$$\frac{14595.6}{490.9} = 29.7 \text{ PSF} \simeq 30 \text{ PSF}$$

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 8-20-87 SHEET 40 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8/21/87 CHECKED [illegible]

PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO.

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME.

AS THE RIGID FOAM FILLS THE OPEN AREA LEFT IN THE FLEXIBLE FOAM LAYER, THE WEIGHT COMPRESSES THE FLEXIBLE FOAM BY THE AMOUNT CALCULATED BELOW.

WT OF RIGID FOAM = 2 PCF

VOL. ELEMENT #	WEIGHT (lbs)	SURFACE AREA $(ft)^2$	LOAD (PSF) $\left(\frac{WT}{AREA}\right)$
1	(2)(332.2) = 664.4	110.7	6
2	(2)(579.6) = 1159.2	96.6	12
3	(2)(742.5) = 1485	82.5	18
4	2(2413.2) = 4826.4	201.1	24
			Σ 60.0

AVG. LOAD = 60/4 = 15 PSF AVG LOAD DUE TO DEAD WT.

AVG DEFLECTION DUE TO DEAD WT. (USE EQN 6)

$\frac{\%\ DEFL}{25\%} \times 129.6 =$ LOAD (PSF) ⇒ SUBSTITUTING 15 PSF FOR LOAD

AVG % DEFL. $= \frac{15}{129.6}(25) = 3\%$

SIMILARLY CALCULATE % DEFL. FOR EXPANSION –

AVG % DEFL (DUE TO EXPANSION) $= \frac{20}{129.6}(25) = 6\%$

THE SUM OF THESE DEFLECTIONS = 9% < 25%.

∴ THE ASSUMPTION OF HOOKE'S LAW IS VALID.

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

5976

ORIGINATOR [signature] DATE 8-12-87 SHEET 41 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED James Campbell

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

APPENDIX #1

ADVANCED SCIENCES, INC.

RECORD OF TELECON

PROJECT: FERNALD FMPC RI/FS CONTRACT: DE-AC05-86OR-21659

FROM D.R. SMITH / J. CAMPBELL OF ASI	FILE	DATE 8/10/87
TO DAVE DRESSEL OF FOAM ENTERPRISES, INC.	JOB NO.	TIME 11:00 AM.

ITEMS OF DISCUSSION	ACTION REQ'D. (INCLUDE NAMES & DATES)
1. BEHAVIOR OF FLEXIBLE FOAM. QUESTION ASKED BY DRS/JC. CAN IT BE ASSUMED THAT THE COMPRESSIVE PRESSURE ON THE FLEXIBLE FOAM AND THE RESULTING DEFLECTION EXHIBIT A LINEAR RELATIONSHIP IN THE RANGE OF 0 TO 25% DEFLECTION (IE. OBEYS HOOKE'S LAW)? ANSWER YES. QUESTION ASKED BY DRS/JC. WHAT CHANGES OCCUR IN THE FLEXIBLE FOAM DURING CURING? ANSWER SINCE THE FLEXIBLE FOAM IS OPEN CELL, THE FOLLOWING FACTS APPLY: 1). THE INTERNAL GASES ARE QUICKLY DISSIPATED. 2). NO PERMANENT VOLUME CHANGE OCCURS DURING CURING. 3). THE HEAT GENERATED DURING CURING IS QUICKLY DISSIPATED. 4). THE TEMPERATURE EFFECTS ON THE FLEXIBLE FOAM (THERMAL EXPANSION / CONTRACTION) CAN BE NEGLECTED.	NONE REQ'D. TELECON INITIATED FOR INFORMATIONAL PURPOSES.

DISTRIBUTION:

DAVE DRESSEL

APPENDIX #2

FOAM ENTERPRISES

13630 Watertower Circle
Minneapolis, MN 55441
(612) 559-3266
(800) 328-3342

1703 Crosspoint
Houston, Texas 77054
(713) 796-9743

CHEMICAL SYSTEM UPC 281

DESCRIPTION: INTEGRAL SKIN FLEXIBLE FOAM

UPC-281 is a MDI based, two component chemical system. This medium low density, open-celled foam has excellent and tough integral skin when cast in metal or plastic molds. It exhibits excellent energy absorption properties over a wide temperature range from 0°F to 150°F. This moderately firm foam is used to package very expensive objects, where flexible cushioning characteristics are needed to dampen shock and resonant freguency encountered in most shipping. It is also recommended for molding arm or head rests for use in furniture, aircraft or automobiles.

CHEMICAL PROPERTIES: (@ 77°F)

Viscosity, CPS	
A-Component: 100	B-Component: 500-600
Specific Gravity	
A-Component: 1.23	B-Component: 1.10
Reactivity Profile	
Cream time, sec.	15-18
Rise time, sec.	30-35
Tack free, sec.	35-40
Mixing Ratio (By Weight) A/B	25/75
Processing Temperature, °F	75-80
Mold Temperature, °F	80-90
Demold Time, min.	10

PHYSICAL PROPERTIES:

Core Density (Free Rise) LB/Ft^3	4
Tensile Strength, PSI	15
Tear Strength, PLI	1.2
Elongation, %	110-120
Resiliency, % ball rebound	60-64
4" ILD, LBS/50 in^2 (based on 4" free rise foam)	
25% Deflection	45 (core)
65% Deflection	98 (core)
Air Flow	3.2

CALCULATION WORKSHEET

ORIGINATOR [signature] DATE 4-11-88 SHEET 43 OF 65

CALC.NO. 60295-01 REV.NO. 1 DATE 4-11-88 CHECKED [signature]

PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

THE PURPOSE OF THE FOLLOWING CALCULATION

IS TO EXAMINE 2 ALTERNATIVE FOAMING SCHEMES WHICH ARE LISTED ON THE FOLLOWING PAGES

THESE CALCULATIONS TAKE INTO ACCOUNT THE DEFLECTION OF THE FLEXIBLE FOAM, AND THEREFORE SHOW PRESSURES SLIGHTLY HIGHER THAN THOSE PREVIOUSLY CALCULATED.

THE CALCULATIONS USE THE FOLLOWING ASSUMPTIONS -

1. FLEXIBLE FOAM DOES NOT EXPAND DURING CURE.
2. MAXIMUM VOLUMETRIC EXPANSION OF RIGID FOAM IS 60%
3. COMPRESSIVE MODULUS OF FLEXIBLE FOAM IS .9 PSI @ 25% DEFLECTION, & THE FLEXIBLE FOAM EXHIBITS A LINEAR RELATIONSHIP BETWEEN 0 & 25% DEFLECTION.
4. RIGID FOAM DENSITY IS 2 PCF.

5. THE CALCULATION ALSO EXAMINES THE EFFECTS OF
   - (A) ALLOWING RIGID FOAM TO CURE SIMULTANEOUSLY OR
   - (B) ALLOWING RIGID FOAM TIME TO UNDERGO ITS EXPANSION / CONTRACTION CYCLE. PRIOR TO PLACING ADDITIONAL FOAM.

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CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 4-11-88 SHEET 44 OF 55

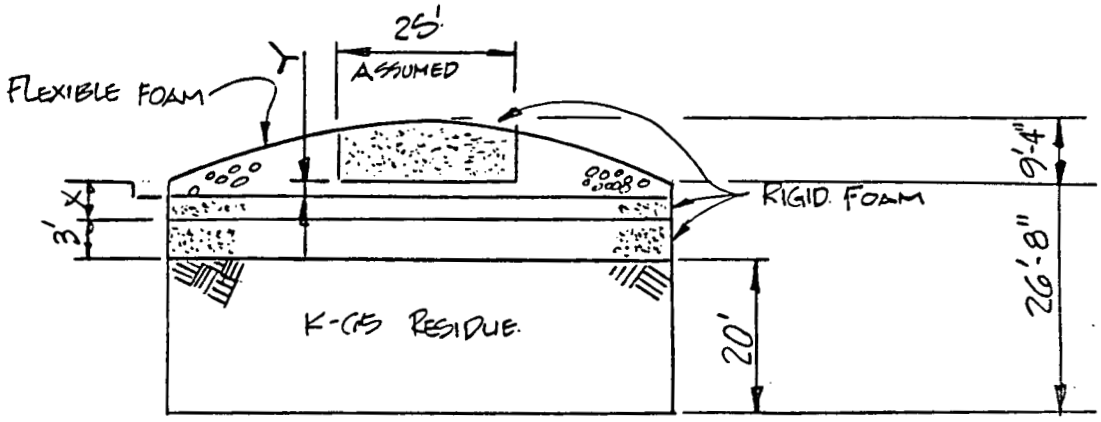
CALC.NO. 60295-01 REV.NO. 1 DATE 4-11-88 CHECKED J. Novak

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

STATEMENT OF PROBLEM:

EXAMINE THE FOAMING SCHEME BELOW TO SEE IF IT POSES ANY PROBLEMS IN RELATIONSHIP TO THE DOME



THIS SKETCH DEPICTS SILO #1

HEIGHT OF DOME TOP = 26'-8" + 9'-4" = 36'-0".

SILO #2 HAS A HEIGHT OF 22'.

ASSUME THE FOLLOWING DIMENSIONS:

X = 2'
Y = 2'

∴ THE THICKNESS OF THE CORE SECTION OF RIGID FOAM ADJACENT TO THE DOME =

$$36 - 20 - (3+2+2) = 9'$$

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CALCULATION WORKSHEET

ORIGINATOR [signature] DATE 4-11-88 SHEET 45 OF 55

CALC.NO. 60295-01 REV.NO. 1 DATE 4/11/88 CHECKED [signature]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

VOLUME OF A LOWER RIGID FOAM LAYER = (3'+2')

$$\frac{\pi d^2}{4} h = \frac{\pi (80)^2}{4} (5) = 25133 \text{ cu ft.}$$

CALCULATE THE CHANGE IN HEIGHT OF THE VOLUME. WHEN THE VOLUME IS EXPANDED 6% $V_E = 1.06(25133) = 26641$.

USING EQN (3) ON PG. 37/42. (ORIGINAL CALCS)

$$h = \sqrt[3]{\frac{V_E (4)}{\pi \, (d_A/h_A)^2}}$$

$$h = \sqrt[3]{\frac{(26641)(4)}{\pi \, (80/5)^2}} = 5.09' \qquad \Delta = .09'$$

CALCULATE THE CHANGE IN HEIGHT OF THE UPPER RIGID FOAM NEXT TO THE DOME.

$$\text{VOLUME} = \frac{\pi (25)^2}{4} (9) = 4418 \text{ cu ft.}$$

EXPANDED VOLUME $(V_E) = 1.06(4418) = 4683$ cu ft.

$$h = \sqrt[3]{\frac{4683 (4)}{\pi \, (25/9)^2}} = 9.16' \qquad \Delta = .16'$$

$$\Delta_{TOTAL} = .16 + .09 = .25' = 3''$$

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CALCULATION WORKSHEET

ORIGINATOR [signature] DATE 4-11-88 SHEET 46 OF 55

CALC.NO. 60295/-01 REV.NO. 1 DATE 4-11-88 CHECKED [signature]

PROJECT FMPC, FERNALD, OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

$\Delta = .25'$ $x = 2'$ $\frac{\Delta}{x} = .25/2 = .13$

LOAD ON DOME (PSF) = $\frac{.13}{.25}(129.6) = \underline{64.8 \text{ PSF}}$

NOTE: SINCE THE UPPER LAYER OF RIGID FOAM ADJACENT TO THE DOME IS CLINDERICALLY SHAPED, THE LOAD ON THE DOME IS A DIRECT CALCULATION.

THIS CALCULATION DID NOT TAKE INTO EFFECT THE DEFLECTION OF THE FLEXIBLE FOAM DUE TO THE WEIGHT OF THE RIGID FOAM ABOVE.

WEIGHT OF RIGID FOAM = 2 PCF.

NOTE: 3 PCF USED ON EXTERIOR DOME. REF:

$2(4418) = 8836^{\#}$ - SURFACE AREA LOADED $= \pi \frac{25^2}{4} = 490.9$

LOAD PSF $= \frac{8836}{490.9} = 18$ PSF.

$\frac{\%\ \text{DEFL}}{25\%} \times 129.6 = \text{LOAD (PSF)}$ ⇒ SUBSTITUTING 18 PSF FOR LOAD

AVG % DEFL. $= \left(18/129.6\right)25 = 3.5\%$.

$.035(2) = .07'$

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ORIGINATOR [illegible] DATE 4-11-88 SHEET 47 OF 55

CALC.NO. 60295-01 REV.NO. DATE 4-11-88 CHECKED J. Novak

PROJECT FMPC FERNALD OHIO INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION FOAM SUPPORT FOR K-65 SILO DOME

TAKE INTO ACCOUNT DEFLECTION OF THE FLEXIBLE FOAM DUE TO THE HT OF THE RIGID FOAM ABOVE.

DEFLECTION DUE TO EXP = +.25'

$X = 2 - .07 = 1.93$

$$\frac{\Delta}{X} = \frac{.25}{1.93} = .13$$

LOAD ON DOME (PSF) = (.3) (129.6) = 67.15 PSF

ALLOW THE 3' OF RIG FOAM SUFFICIENT TIME TO CURE

CALCULATE THE LOAD ON DOME. ASSUMING 3' OF FOAM DOES NOT EXPAND (SINCE IT IS ALLOW TO CURE).

CALCULATE Δ FOR 3 FOAM AND SUBTRACT IT FROM THE TOTAL.

$$VOL = \pi \frac{(80)^2}{4}(3) = 15080 \text{ cu ft.}$$

$$V_E = 15080\ (1.06) \quad 5984.8 \text{ cu ft.}$$

$$h = \sqrt[3]{\frac{(15984.8)(4)}{\pi\ (80/3)^2}} = 3.055'' \qquad \Delta = .055''$$

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CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 4-11-88 SHEET 48 OF 55

CALC.NO. 60295-01 REV.NO. DATE 4-11-88 CHECKED J. Novak

PROJECT FMPC FERNALD OHIO GS INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION FOAM SUPPORT FOR K-65 SILO DOME

Δ_{TOTAL} (INCLUDING DEFLECTION OF FLEX FOAM) = .25

SUBTRACT THE Δ FOR 3' OF RIGID .055

NEW Δ .195

CALCULATE THE LOAD ON THE DOME (PSF) FOR THIS CASE

$$\frac{\Delta}{x} = \frac{.195}{1.93} = .101$$

LOAD ON DOME (PSF) = $.101/.25\ (129.6) =$ 52.38 PSF

REPEAT THE PROCESS FOR A 3' FLEXIBLE FOAM LAYER. ASSUMING THE FOAM IS PLACED AT RELATIVELY THE SAME TIME.

Δ 5' RIGID LAYER = .09'

THE UPPER RIGID LAYER NOW IS ONLY 8' HIGH.

$$\text{VOLUME} = \frac{\pi(25)^2}{4}(8) = 3927 \text{ cu ft.}$$

$$V_E = 1.06(3927) = 4163 \text{ cu ft.}$$

$$h = \sqrt[3]{\frac{(4163)(4)}{(\pi)\ (25/8)^2}} = 8.14' \qquad \Delta = .14'$$

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CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 4-11-88 SHEET 49 OF 55

CALC.NO. 60295-01 REV.NO. 1 DATE 4-11-88 CHECKED [illegible]

PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

$\Delta_{TOTAL} = .14 + .09 = .23'$

WEIGHT OF RIGID FOAM = 3927 (2) = 7854 #.

WEIGHT (PSF) = $7854 / \left(\pi \frac{(25)^2}{4}\right) = 7854 / 490.9 = 15.993 \approx 16$ PSF

$\frac{\%\ DEFL}{25\%} \times 129.6 =$ LOAD (PSF) SUBSTITUTING 16 PSF FOR LOAD

AVG. % DEF = $\left(16/129.6\right)(25) = 3.1\%$

$.031\ (3) = .093'$

$X = 3' - .093' = 2.907'$

CALC LOAD ON DOME.

$\frac{\Delta}{X} = \frac{.23}{2.907} = .079$

LOAD ON DOME (PSF) = $.079/.25\ (129.6) = \underline{41.01\ \text{PSF.}}$

IF THE 3' LAYER IS ALLOWED TO CURE BEFORE ADDITIONAL PLACEMENT OF FOAM, CALCULATE THE LOAD ON THE DOME.

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CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 4-11-88 SHEET 50 OF 55

CALC.NO. 60295-01 REV.NO. 1 DATE 4-11-88 CHECKED J. Novak

PROJECT FMPC FERNALD, OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

Δ (3' RIGID FOAM) = .055" (SEE PG)

$$\begin{array}{r} .23' \\ -\ .055' \\ \hline .175' \end{array}$$

$$\frac{\Delta}{x} = \frac{.175'}{2.907} = .06$$

LOAD ON THE DOME = $.06/.25\ (129.6) = \underline{\underline{31.2 \text{ PSF}}}$

ASSUME A 1.2" MAXIMUM DOME MOVEMENT

CALCULATE THE LOAD IN PSF ON THE DOME

WITH A 3' LAYER OF FLEXIBLE FOAM.

$$\frac{1.2}{12} = .1'$$

$$\frac{.1}{2.907} = .034$$

LOAD (PSF) = $.034/.25\ (129.6) = 17.83$ PSF.

CALCULATE THE LOAD DUE TO A 1.2" DOME MVMT AND 2' OF FLEXIBLE FOAM. (ASSUME THE 2' LAYER IS DEFLECTED DUE TO THE WEIGHT)

$$\frac{.1}{1.93} = .052 \qquad .05/.25\ (129.6) = 26.86 \text{ PSF.}$$

NOTE: SINCE THE DOME IS INSULATED, THIS MOVEMENT IS CONSERVATIVE.

CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 4-11-88 SHEET 51 OF 55

CALC.NO. 60295-01 REV.NO. 1 DATE 4-11-88 CHECKED [illegible]

PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

CONCLUSIONS AND OBSERVATIONS

1. USING A LAYER OF FLEXIBLE FOAM 2' THICK WILL NOT BE ACCEPTABLE.

2. USING A LAYER OF FLEXIBLE FOAM 3' THICK WILL BE ACCEPTABLE IF THE INITIAL RIGID FOAM LAYER IS ALLOWED TO CURE BEFORE PLACEMENT OF RIGID FOAM.

4. A MODULUS OF .9 PSI OF FLEXIBLE FOAM WAS USED. THE SLIGHTEST UPWARD DEVIATION IN THIS VALUE WILL CAUSE A RATHER DRASTIC CHANGE IN THE LOAD APPLIED TO THE DOME DURING EXPANSION.

5. IF CONTACT BETWEEN THE DOME AND FOAM IS LOST, NO STRUCTURAL SUPPORT FOR THE DOME IS PROVIDED. THIS COULD HAPPEN IF ALL FOAM IS PLACED AT RELATIVELY THE SAME TIME.

6. THESE CALCS REPRESENT SILO #1. SIMILIAR RESULTS COULD BE ACHIEVED FOR SILO #2 BY ELIMINATING THE 2' RIGID FOAM PLACED ABOVE THE 3' RIGID FOAM LAYER.

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CALCULATION WORKSHEET

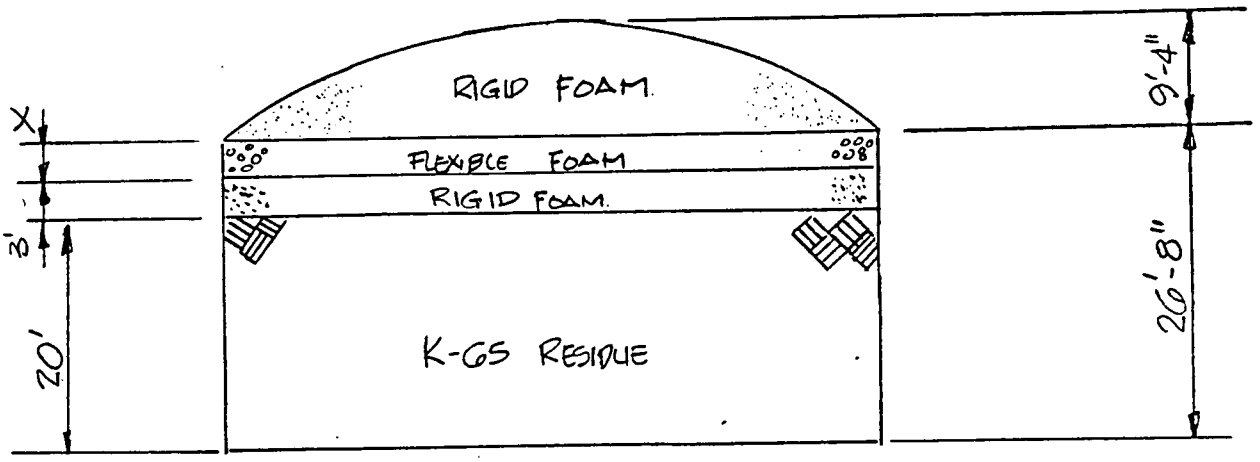
ORIGINATOR [illegible] DATE 4-11-88 SHEET 52 OF 55

CALC.NO. 60295-01 REV.NO. 1 DATE 4-11-88 CHECKED J. Novak

PROJECT FMPC FERNALD OU10 K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

EXAMINE THE FOLLOWING SCENERIO.



THIS SKETCH DEPICTS SILO #1

HEIGHT OF DOME TOP = 36'-0"

ASSUME X = 3'-0".

THE MAX. THICKNESS OF RIGID FOAM UNDERNEATH THE CENTER OF THE DOME = 36 - 20 - 3 - 3 = 10'

OTHER ASSUMPTIONS:

RIGID FOAM EXPANDS IN VOLUME A MAXIMUM OF 6%.
MODULUS OF COMPRESSION OF FLEX. FOAM = .9 PSI = 129.6 PSF
FLEXIBLE FOAM DOES NOT EXPAND IN VOLUME AFTER INSTALLATION.

CALCULATION WORKSHEET

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ORIGINATOR [signature] DATE 4-11-88 SHEET 53 OF 55

CALC.NO. 60295-01 REV.NO. 1 DATE 4-11-88 CHECKED J. Novak

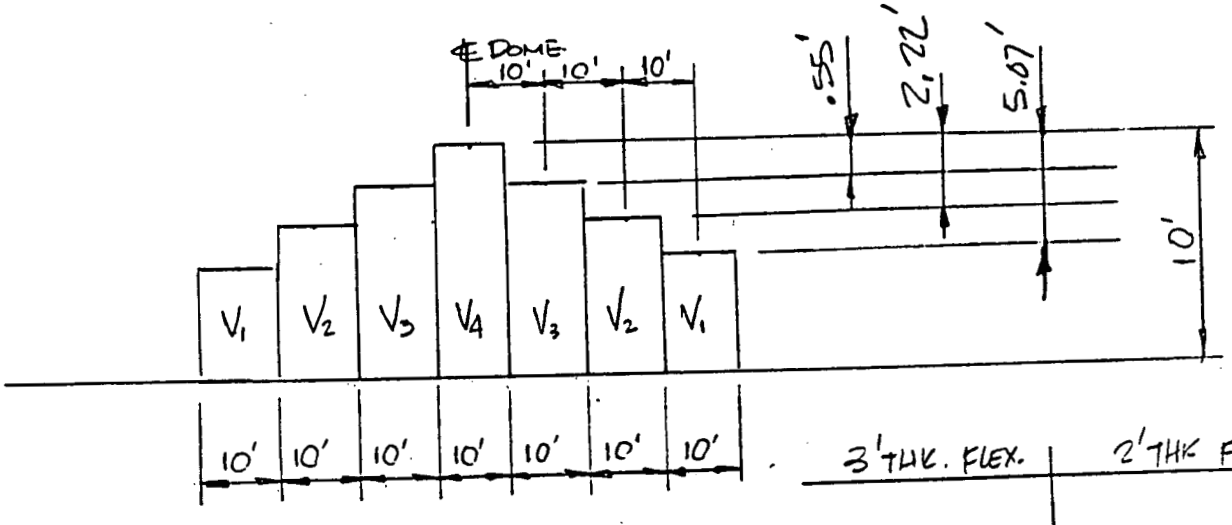
PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME.

MODEL THE FOAM AS CONCENTRIC VOLUMES (AS BEFORE, SEE PG 27/43)

USE EQNS 3 & 4 TO CALCULATE THE CHANGE IN HEIGHT.

ASSUME A 70' ϕ AREA (THE HEIGHT OF FOAM AT THE EDGES OF THE DOME ARE NOT AS TALL AND WILL EXPAND LESS. THEREFORE THEY ARE NOT CONSIDERED.



		3' THK. FLEX.	2' THK FLEX.
HEIGHT OF V_1 = 10 - 5.07 = 4.93'	≃	5'-0" = h	6'-0"
HEIGHT OF V_2 = 10 - 2.22 =	∴	7.78' = h	8.78'
HEIGHT OF V_3 = 10 - .55 =		9.45' = h	10.45'
V_4 = 10' =		10' = h	11.0'

V_1 - d_i = 50 d_o = 70
V_2 - d_i = 30 d_o = 50
V_3 - d_i = 10 d_o = 30
V_4 - d = 10.

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CALCULATION WORKSHEET

ORIGINATOR [signature] DATE 4-11-88 SHEET 54 OF 55

CALC. NO. 60295(1-01) REV. NO. 1 DATE 4-11-88 CHECKED [signature]

PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

AVERAGE DOME LOAD FOR A 3' FLEX LAYER.

NOTE: THIS DOES NOT INCLUDE SIMULANEOUS EXPANSION OF THE LOWER LAYER OF RIGID FOAM.

Vol. #	(1) ft^2	(2) ft^3	(3) ft^3	4 ft.	5 (ft.)	6 ft.	7 (PSF)	8 (PSF)	9 %	10 FT	11 (PSF)	(12) lb.
1	1884.96	9424.78	9990.27	5.09	.09	2.91	16.03	10.6	2	2.85	16.37	30861.5
2	1256.64	9776.64	10363.24	7.92	.14	2.86	25.38	16.49	3.2	2.77	26.25	32989.77
3	628.32	5937.61	6293.87	9.61	.16	2.84	29.21	20.03	3.9	2.72	30.45	19131.49
4	78.54	785.40	832.52	10.17	.17	2.83	31.14	20.0	3.9	2.71	32.47	2550.08

Σ 3848.46 Σ. 85537.84

Col. #1.- SURFACE AREA. $\pi/4\, d^2$ OR $\pi/4\,(d_o^2 - d_i^2)$
col #2. SURFACE AREA (h). = Vol.
col #3. EXPANDED VOLUME - Vol X1.06.
col #4. NEW h. (EQN 3 OR 4). SEE PG. 37/42 OF ORIGINAL CALCS.
col #5. Δh.
col #6. $x = 3 - \Delta h$.
col #7 LOAD ON DOME IN PSF (DUE TO RIGID FOAM EXPANSION) $\left[\left(\text{col } 5/\text{col } 6\right) \div .25\right] 129.6$
col #8 WEIGHT OF RIGID FOAM VOLUME ÷ SURFACE AREA (COL #1) DENSITY ASSUMED = 2 PCF.
Col #9 % DEFLECTION OF FLEXIBLE FOAM DUE TO DL OF RIGID. $\left(\frac{\text{WEIGHT}}{129.6}\right) 25 = \%$ DEFL.
col #10 TOTAL DEFLECTION OF FLEXIBLE FOAM DUE TO DL + RIGID FOAM EXPANSION.
col #11 $\left[\left(\text{col } \#5/\text{col } \#10\right) \div .25\right] (129.6)$ = LOAD ON DOME (psf) INCLUDING EFFECTS OF DL DEFL OF FLEXFOAM.
col #12 col #11 X col #1.

AVERAGE LOAD ON DOME (INCLUDING DL EFFECTS) = 22.22 PSF.

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CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 4-11-88 SHEET 65 OF 55

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PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

AVERAGE DOME LOAD FOR A 2' FLEX. LAYER

NOTE: THIS DOES NOT INCLUDE SIMUTANEOUS EXPANSION OF THE LOWER LAYER OF RIGID FOAM.

#	(1) ft^2	(2) ft^3	(3) ft^3	(4) ft	(5) ft	(6) ft	(7) PSF	(8) PSF	(9) %	(10) FT	(11) PSF	(12) lb.
1	1884.96	11309.76	11988.35	6.107	.107	1.89	29.35	12.0	2.3	1.84	30.15	56831.71
2	1256.64	11033.3	11695.3	8.93	.153	1.85	42.87	18.61	3.6	1.78	44.61	56051.80
3	628.32	6565.94	6959.90	10.63	.18	1.82	51.27	22.15	4.3	1.735	53.80	33,803.44
4	78.54	863.94	915.78	11.19	.19	1.81	54.42	23.32	4.5	1.72	57.26	4497.52

Σ 3848.46 Σ 151184.47

AVERAGE LOAD ON DOME DURING EXPANSION = $\frac{151184.47}{3848.46}$

= 39.28 PSF

INCLUDES EFFECTS OF DEAD WT OF RIGID FOAM

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5976

4.0

STRUCTURAL ASSESSMENT
K-65 Storage Silos Radon Mitigation and Dome Reinforcement

August, 1987
Revision 0

Prepared for:
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Company of Ohio

Prepared by:
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1. Cross-Sectioned Arrangement of Foam Fill 6

feet high. The silo domes were originally designed to be 8 inches thick at the dome wall tapering to 4 inches thick at the center.

The walls were post-tensioned reinforced with 0.162-inch-diameter wire stressed to 140,000 pounds per square inch (PSI) (with assumed 30% loss, for a design stress of 100,000 PSI). These post-tensioning wires were covered by a 3/4-inch-thick gunite coating. The minimum 28-day compressive strength used was 4,500 PSI for the dome and walls and 3000 PSI for the floor and footing. The maximum allowable soil pressure was 4000 pounds per square foot (PSF).

The silos were designed to be loaded with the metal oxides in slurry form at a maximum rate of 8000 gallons per day. The radioactive residues were allowed to settle and the water was decanted, leaving a sludge with a density of 100 pounds per cubic foot (PCF) and angle of repose of 0 degrees. The maximum allowable height of solid material was 23 feet and the water was decanted to a plant to be reused in the production of additional slurry.

In 1963, the silos were showing signs of exterior surface deterioration. Large areas of spalling occurred in the exterior surface gunite coating, particularly on the north silo, leaving post-tensioning wires exposed to weather. Subsequently, patches of the wires became severely corroded and broken. Various options were investigated as remedial actions for the silos. Repairs began in 1964 by first chipping away all loose gunite material and then patching the surface with 3/4 inch coat of cement mortar. After the gunite was repaired, and a waterproofing sealant was applied to the external silo walls, an earth embankment was built to the top of the wall on a one and one-half to one (1-1/2:1) slope (horizontal:vertical). The earthen embankment was to provide relief from tensile stress within the walls by counterbalancing the load from the internal contents, since the broken wires were not replaced. A soil was chosen with roughly the same density (125 PCF) as the contents of the silos (100 PCF). Two additional purposes of the embankment were to provide weather protection and to reduce the radon emission from the silos.

In the subsequent years problems with soil erosion on the soil embankment were frequent. The eroded areas were repaired, but with heavy rains the problem reoccurred. In 1983, the embankment was enlarged to achieve a 3:1 slope. No further evidence of large scale erosion has occurred.

In February 1986 a structural analysis of the silos was completed by Camargo Associates, LTD. (CAMARGO) (Reference 2) The analysis included a field investigation of the silos to determine their condition which was completed in September 1985. Information gathered from this investigation was used in a computer model to assess the structural integrity of the silos. The conclusions reached in the CAMARGO report are as follows:

1. The base slab and walls at this time are structurally stable under the existing static loads being applied to them and should continue to be so for approximately 5 to 10 years.

2. If either the contents of the silos or the silo embankment are removed, they must be removed simultaneously or failure of the walls or base slab could result.

3. The center 20 foot diameter portion of the dome top is structurally unsound for a load greater than the existing static dead load and no life expectancy can be assigned to it.

4. The application of a three foot thick earth fill load on the dome or the application of tornado suction or pressure loads, would cause a structural failure of the dome.

5. The application of the "defined" synthetic earthquake would induce some additional cracking in the base slab and at the base of the silo wall, but the silo would still be in a serviceable condition. The dome would be unaffected, and should simply move with the ground motions.

6. If a cover is chosen to cover the center portion of each silo dome, the weight should be as light as possible and in no case should it be greater than that allowed by the buckling capacity of the dome (approximately 11,000 pounds).

Based upon the recommendations made by CAMARGO, a temporary cap consisting of steel members and plywood sheathing was placed on the center 30-foot-diameter portion of each K-65 Silo. The details of the caps are depicted in Reference 3. The information in this section represents the current status of the domes.

Due to the time constraints on this project, an additional in-depth structural analysis was not performed on the silos. The CAMARGO report (Reference 2) was used as a basis for the structural assessment of the proposed dome reinforcement.

1.2 STATEMENT OF PROBLEM

Due to environmental elements, the K-65 Silo domes have deteriorated and are considered the weakest structural component of the silo system. The placement of the dome covers over the structurally defective center 20 foot portion of the domes was considered only as a short-term remedial solution (1-2 years). Since final remediation plans for the K-65 Silos will take at least three years to develop and implement, it is necessary to take additional remedial action to provide for continued safe-containment of the K-65 residues.

1.3 SOLUTION

A proposal was made as outlined in Reference 5 to fill void space in each dome with closed cell rigid polyurethane foam. This solution was chosen because (1) radon gas is attenuated by the foam and (2) the rigid foam acts as structural support for the dome.

The major drawback of using rigid foam exclusively is that it tends to expand in volume after application. The uncertainty in the amount of expansion leads to the possibility that the rigid foam could expand to the point of applying an excessive upward load possible causing structural failure to the dome.

Therefore, it is desirable to use rigid foam in conjunction with an open celled, flexible foam. The impact of rigid foam expansion on the structure is lessened due to the low compression modulus of the flexible foam (See Figure 1 for the cross-sectional arrangement of the foam fill). The foam arrangement consists of the following: a sealing membrane over the K-65 residue, a two-foot layer of rigid foam on top of the membrane, flexible foam filling the silo except for center 25-foot diameter portion, rigid foam in the uppermost center portion, and 2 inches of rigid foam covering the outer portion of the dome for insulation purposes. The temporary cap would be left in place and covered with rigid foam. A weatherproofing membrane would be placed on the exterior layer of foam.

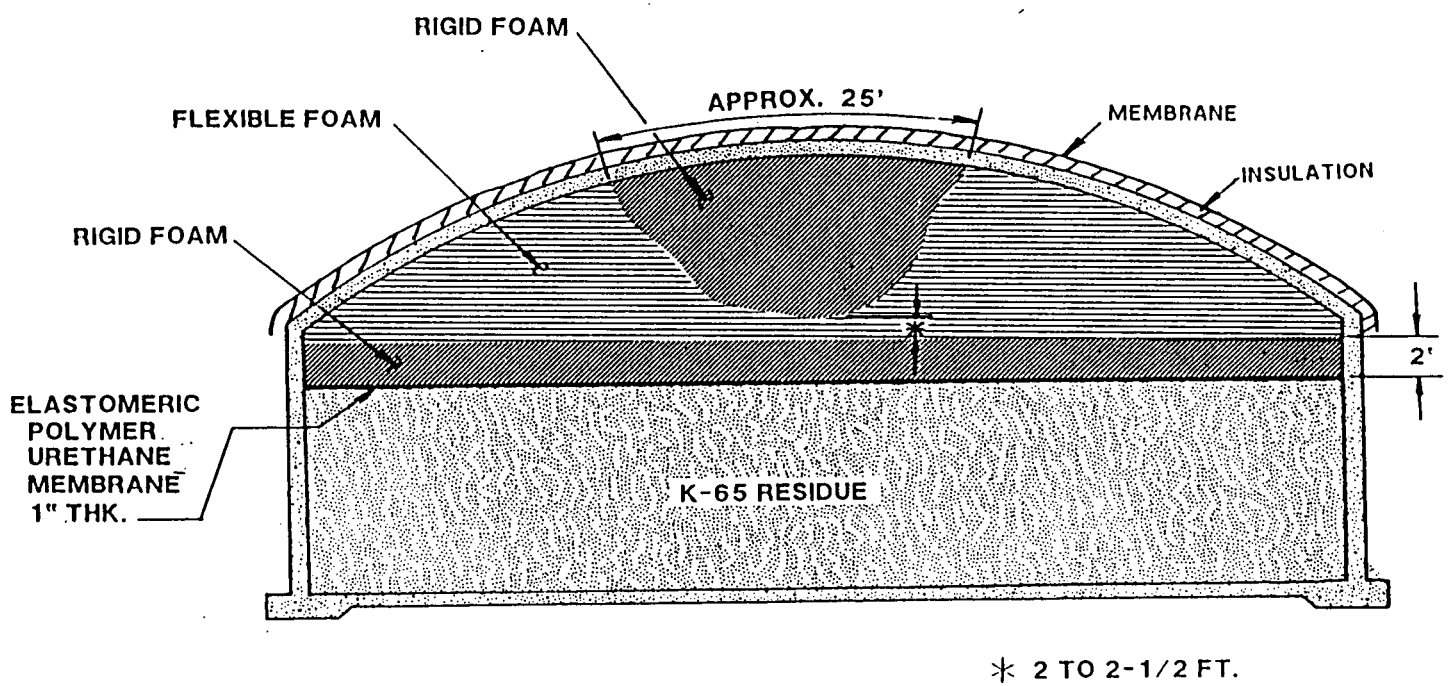

FIGURE 1

CROSS-SECTIONAL ARRANGEMENT OF FOAM

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2.0 STRUCTURAL ASSESSMENT

2.1 ASSESSMENT OF THE WEIGHT OF THE PROPOSED FOAM MATERIAL AND ITS LOADING EFFECT ON THE FOLLOWING: SIDE WALLS, EARTH BERMS, FOUNDATION (FLOOR), AND K-65 MATERIAL

The additional weight produced by the installation of the foam material is estimated to be less than 3% of the weight of the K-65 residue inside the silos. This is based on information provided by the foam vendor (Reference 4). The CAMARGO Report (Reference 2) states that the walls are in compression in their present static state. This increase in weight due to foam addition should not alter the present state of the walls, due to the small percentage change in weight. The same is true for the foundation and earth berm. Under dynamic forces induced by an earthquake, load redistribution would occur due to cracks developing in the concrete walls and floor. Again, due to the small percentage change in weight from the foam addition, the conclusions reached in the CAMARGO Report should not change. The foam should have no adverse effect on the K-65 material provided the foam is uniformly applied.

2.2 EXPECTED THERMAL EXPANSION AND CONTRACTION CHARACTERISTICS OF THE FOAM MATERIAL, AND THE RESULTING STRUCTURAL EFFECTS ON THE SILO STRUCTURE DUE TO FOAM EXPANSION AND CONTRACTION

2.2.1 General Characteristics Of Rigid Foam As Applicable To This Project

Rigid foams exhibit a variety of characteristics depending upon density, temperature, blowing agents, foaming system and relative humidity. Dimensional stability (i.e. percent volume change) varies depending on these parameters. The foam selected for this application is MG2-B of Foam Enterprises. Selection was based on strength, radon attenuation, and availability. The foam is formed by an exothermic reaction of liquid chemicals with initial set occurring a few minutes after mixing. After initial set, the foam exhibits a continued rise in temperature, resulting in an increase in volume. As the foam cools, shrinkage begins to occur.

Eventually the foam volume will return to its original volume or shrink an additional 1 to 2 percent. The foam may also expand/contract due to ambient temperature changes after curing. Rigid foam exhibits excellent insulation characteristics and a compressive strength of approximately 24 PSI at 10 percent deflection.

2.2.2 General Characteristics Of Open-Celled, Flexible Foam As Applicable To This Project

Since the flexible foam is an open-celled foam, the heat generated during curing is quickly dissipated. No significant volume change occurs during curing and thermal expansion/contraction can be neglected. The foam selected is UPC 281 of Foam Enterprises with a modulus of 0.9 PSI at 25 percent deflection.

2.2.3 Structural Effects Of The Foam On The Silo Structure

The rigid foam expansion during curing presents a problem as previously mentioned. However, when applied in conjunction with an open-celled flexible foam, the initial expansion/contraction of the rigid foam should be absorbed by the flexible foam with no adverse effects expected on the walls, foundation, or other parts of the structure excluding the dome which is discussed below.

A maximum expansion of 6 percent is expected for the rigid foam, which produces an average 6 percent deflection in the flexible foam, resulting in a pressure of approximately 30 PSF on the dome. Expansion of the foam during curing is uncontrolled and not easily predicted. Should additional expansion occur dome cracking and uplift may result.

The insulating layer of rigid foam that is applied to the dome exterior will dampen the dome thermal movement by reducing temperature fluctuations resulting in an extended dome life. The insulation also reduces temperature change of air in the open-celled foam and the associated forces caused by

increased air pressure.

Vertical thermal movement of the dome is estimated to be 1 inch. A 2-foot layer of flexible foam depressed one inch will induce a load of 22 PSF. The weight of the dome in the center portion is approximately 25 PSF. Therefore the forces exerted on the dome due to temperature contraction of the dome will approximately balance the dome weight. However because the dome movement is resisted by the foam additional tensile stresses will be induced in the dome which will increase cracking. This cracking will result in decreased life; however, the consequences of failure are lessened by the foam installation as is discussed below.

2.3 ANALYSIS OF THE ABILITY OF THE FOAM MATERIAL TO FUNCTON AS STRUCTURAL SUPPORT FOR THE DOME

The flexible foam itself provides little or no structural support. The flexible foam will be applied under the dome except for an approximate 25-foot-diameter area under the weak center portion. The outer area of the dome is considered to be more structurally stable than the critical 20-foot-diameter center portion and no additional structural support is required.

A core of rigid foam, in combination with at least 2 feet of flexible foam as shown in Figure 1, will be placed under the center 20-foot-diameter portion of the dome. This combination is capable of sustaining the dead weight of the 20-foot-diameter portion of the dome plus a snow load of 20 PSF with a deflection of 1 to 2 inches at center should collapse of the 20-foot-diameter portion occur. Structural support of the center 20-foot-diameter dome portion prior to collapse is difficult to predict without an extensive investigation. Estimating support is complicated by the shrinkage characteristics of the foam. If the foam shrinks beyond its initial set volume, contact with the dome will be lost and no support will be provided prior to collapse.

However, foam placed inside the dome in conjunction with a combination of a rigid foam insulating layer plus a weather-proofing membrane applied to the

4. The combination of rigid/flexible foam allows for thermal movement of the dome. Thermal expansion/contraction of the flexible foam is projected as minimal, and the flexible foam can absorb expansion/contraction of the rigid foam with minimal impact to the silo.

2.5.2 Drawbacks

1. Implementation of the foam system does not preclude advanced cracking of the dome, or even dome failure. It is recommended that additional weight be kept off the center portion of the dome during the foaming operation.

2. Thermal expansion of the foam during curing will produce an upward load on the dome. The load is projected to be within acceptable limits, however unpredicted additional expansion may result in dome cracking.

2.6 GENERAL COMMENTS

If the center portion of the dome collapses, the structural integrity of the remaining portion of the dome is questionable. The proposed foam installation does not provide support for the outer portion of the dome.

It is recommended that the temporary cover (cap) remain in place. Rigid foam insulation should be applied to both the exterior portion of the 30-foot-diameter center portion of the dome (inside the cover) and to the cover itself. The weatherproofing membrane should be applied to all exterior dome and cap surfaces.

It is also recommended that the 11,000 lb load limit specified in the CAMARGO report not be exceeded since insulation added to the dome plus the temporary cover (cap) nearly equals this limit.

2.7 REFERENCES

1. Original design drawings prepared by Preload Enterprises, Inc. 51T20 series and 51T29 series issued in 1951.

2. "K-65 silos study and evaluation for the feed materials production center" CARMAGO Associates Limited February 25, 1986.

3. Design Drawings. "Temporary protection cover system for K-65 tanks" prepared by CAMARGO Associates Limited 12/16/85.

4. Material data sheets provided by Foam Enterprises.

5. Conceptual Design Report, K-65 Storage Silo Radon Mitigation and Dome Reinforcement Study, Joseph T. Grumski, Westinghouse Materials Company of Ohio, May 1987. Revision 1.

APPENDIX A.

CALCULATION WORKSHEET

5976

ORIGINATOR [illegible] DATE 8-12-87 SHEET 1 OF VI

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED James Campbell

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

PURPOSE

THE PURPOSE FOR THIS CALCULATION IS TO INVESTIGATE THE STRUCTURAL BEHAVIOR OF THE K-65 CONCRETE SILO WHEN FILLED WITH A COMBINATION OF FLEXIBLE AND RIGID FOAM IN THE REGION BETWEEN THE CONTENTS AND THE DOME. THE EFFECTS OF THE ADDED WEIGHT OF THE FOAM ON THE SILO, PLUS THE EFFECTS OF THE FOAM ON DOME THERMAL MOVEMENT ARE EXAMINED, AS WELL AS THE ABILITY OF THE RIGID FOAM TO SUSTAIN LOADS.

STATEMENT OF PROBLEM

DETERMINE THE EFFECTS OF ADDING A COMBINATION OF RIGID AND FLEXIBLE FOAM ON THE K-65 CONCRETE SILO.

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CALCULATION WORKSHEET

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SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

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1) MARKS' STANDARD HANDBOOK FOR MECHANICAL ENGINEERS
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2) PRINCIPLES OF HEAT TRANSFER
FRANK KREITH
3rd EDITION (HARPER & ROW)

3) THERMAL ENVIRONMENTAL ENGINEERING
JAMES L. THRELKELD
2nd EDITION (PRENTICE - HALL)

4) MODERN MATERIALS SCIENCE
IRVING GRANET
1st EDITION - 1980 (RESTON)

5) STEEL CONSTRUCTION MANUAL
AMERICAN INSTITUTE OF STEEL CONSTUCTION INC.
8th EDITION

6) HANDBOOK OF MATHMATICAL, SCIENTIFIC, AND ENGINEERING FORMULAS, TABLES, FUNCTIONS, GRAPHS, TRANSFORMS
RESEARCH AND EDUCATIONAL ASSOCIATION
1986

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SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

REFERENCES - CONT.

7) ORIGINAL DESIGN DRAWINGS
PRELOAD ENTERPRISES, INC.
5/T20 SERIES AND 5/T29 SERIES
ISSUED IN 1951

8) "K-65 SILOS STUDY AND EVALUATION FOR THE FEED MATERIALS PRODUCTION CENTER"
CAMARGO ASSOCIATES LIMITED
FEBRUARY 25, 1986

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CALCULATION WORKSHEET

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

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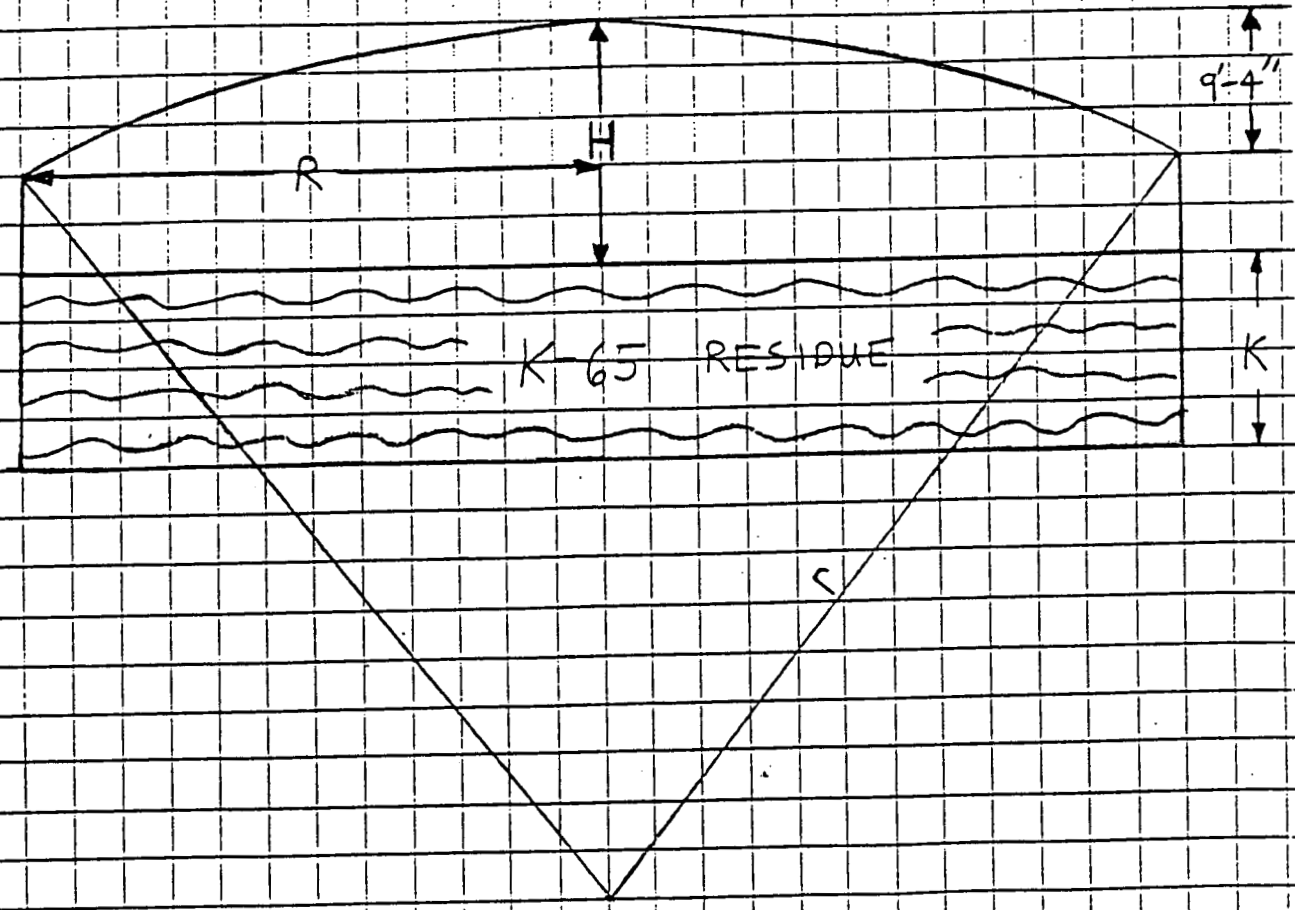
PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



SKETCH OF DOME GEOMETRY

SILO #1	SILO #2
R = 40'	R = 40'
H = 15'-7"	H = 13'-7"
K = 20'	K = 22'

$b = 9'-4" = 112"$

$c = 2R = 80' = 960"$

$r = (4b^2 + c^2)/8b$

$r = (4(112)^2 + (960)^2)/8(112)$

$r \cong 1{,}084.6"$

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SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

DOME WEIGHT

ASSUMPTION - THE FOAM MUST SUPPORT THE ENTIRE WEIGHT OF THE DOME (EXCLUDING THE OUTER 2').

	DOME SECTION	THICKNESS	VOLUME $\pi(R^2-r^2)h$ (REF. #1 P. 2-13)
20'Ø CENTER	4'Ø	2"	$\pi(2)^2(\frac{2}{12}) = 2.09\ ft^3$
	4'Ø to 18.16'Ø	2½"	$\pi((9.08)^2-(2)^2)(\frac{2.5}{12}) = 51.34\ ft^3$
	18.16Ø to 20'Ø	3"	$\pi((10)^2-(9.08)^2)(\frac{3}{12}) = 13.79\ ft^3$
	20'Ø to 33.16'Ø	3"	$\pi((16.58)^2-(10)^2)(\frac{3}{12}) = 137.36\ ft^3$
	33.16'Ø to 41.34'Ø	3½"	$\pi((20.67)^2-(16.58)^2)(\frac{3.5}{12}) = 139.60\ ft^3$
	41.34Ø to 56'Ø	4"	$\pi((28)^2-(20.67)^2)(\frac{4}{12}) = 378.59\ ft^3$
	56'Ø to 64'Ø	4½"	$\pi((32)^2-(28)^2)(\frac{4.5}{12}) = 282.74\ ft^3$
	64'Ø to 76'Ø	5"	$\pi((38)^2-(32)^2)(\frac{5}{12}) = 549.78\ ft^3$

TOTAL VOLUME = 1,550.29 ft^3

TOTAL WEIGHT (@ 150 pcf) = 1,550.29 × 150 = 232,544 lbs

VOLUME OF 20'Ø CENTER = 2.09 + 51.34 + 13.79 = 67.22 ft^3

WEIGHT OF 20'Ø CENTER = 67.22 × 150 = 10,083 lbs

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DOME - LIVE LOAD

ASSUMPTION - 20 psf LIVE LOAD (PRIMARILY SNOW) AS STATED IN THE CAMARGO REPORT (REF #8 P. 27)

SURFACE AREA OF THE DOME = $2\pi rh$ (REF. #6 P. 145)

$r = 1{,}084.5'' = 90.38'$

$h = 9'-4'' + 2'' = 9'-6'' = 114''$

$A = 2\pi(90.38)(9.5) = 5{,}395\ ft^2$

LIVE LOAD = 20 psf x $5{,}395\ ft^2$ = $\boxed{107{,}900\ lbs}$

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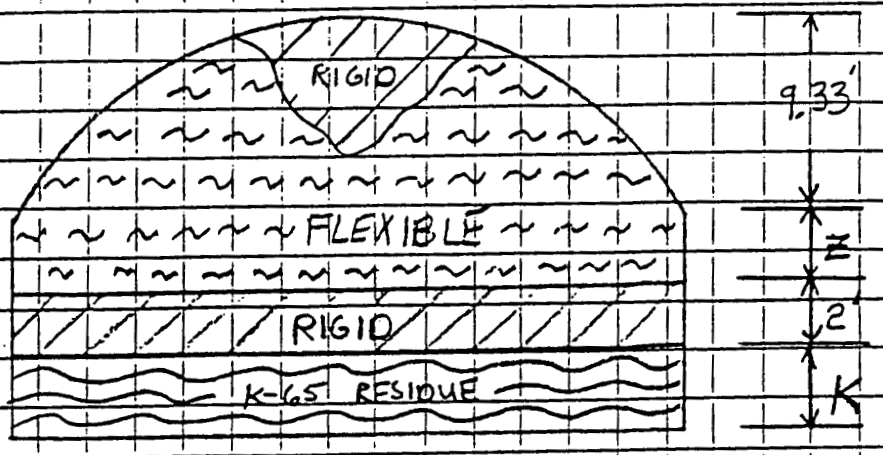

SKETCH OF FOAM GEOMETRY

SILO #1	SILO #2
K = 20'	K = 22'
Z = 3'	Z = 1'

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CALCULATION WORKSHEET

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SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

FOAM VOLUME

SILO #1

$V_{RIGID} = \pi(40)^2(2)$ (REF #1 P.2-12)

$V_{RIGID} = 10{,}053\ FT^3$

(REF #6 P.145) $V_{FLEX}^{*} = \pi(40)^2(z) + \frac{1}{3}\pi(9\frac{1}{3})^2(3(R) - 9\frac{1}{3})$

WHERE $R = 90.38'$; $z = 3'$

$V_{FLEX} = \pi(40)^2(3) + \frac{1}{3}\pi(9\frac{1}{3})^2(3(90.38) - 9\frac{1}{3})$

$V_{FLEX} = 15{,}080 + 23{,}883$

$V_{FLEX} = 38{,}963\ FT^3$

SILO #2

$V_{RIGID} = \pi(40)^2(2)$

$V_{RIGID} = 10{,}053\ FT^3$

$V_{FLEX} = \pi(40)^2(z) + \frac{1}{3}\pi(9\frac{1}{3})(3(R) - 9\frac{1}{3})$

WHERE $R = 90.38'$; $z = 1'$

$V_{FLEX} = \pi(40)^2(1) + \frac{1}{3}\pi(9\frac{1}{3})(3(90.38) - 9\frac{1}{3})$

$V_{FLEX} = 5{,}027 + 23{,}883$

$V_{FLEX} = 28{,}910\ FT^3$

THIS CALCULATION ASSUMES ALL FLEXIBLE FOAM ABOVE A 2' LAYER OF RIGID. THIS IS CONSERVATIVE FOR WEIGHT CALCULATIONS BECAUSE FLEXIBLE FOAM WEIGHS 5 pcf COMPARED TO 2 pcf FOR THE RIGID.

* V_{FLEX} IS THE VOLUME OF THE FLEXIBLE FOAM PLUS THE VOLUME OF RIGID UNDER THE CENTER OF THE DOME.

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 6 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

FOAM WEIGHT

WORST CASE (SILO #1)

$V_{RIGID} = 10{,}053\ FT^3$

$\rho_{RIGID} = 2\ pcf$

$W_{RIGID} = (10{,}053) \times (2) = 20{,}106\ LBS.$

$V_{FLEX} = 38{,}963\ FT^3$

$\rho_{FLEX} = 5\ pcf$

$W_{RIGID} = (38{,}963) \times (5) = 194{,}815\ LBS.$

TOTAL FOAM WEIGHT = 20,106 + 194,815

TOTAL FOAM WEIGHT = 214,921 LBS. $\boxed{\sim 215{,}000\ LBS.}$

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 7 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

TOTAL WEIGHT

DOME WEIGHT = 232,544 lbs

DOME LIVE LOAD = 107,900 lbs

FOAM WEIGHT = 215,000 lbs

TOTAL WEIGHT = 555,444 lbs ~ 555,000 lbs

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CALCULATION WORKSHEET

ORIGINATOR Jance Campbell DATE 8-12-87 SHEET 8 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

VERTICAL WALL

K-65 RESIDUE WEIGHT $= \pi(40)^2(20) \times 100$ pcf
$= 10{,}053{,}096$ lbs. (SILO #1)

DOME WEIGHT (DL + LL) = 340,444 lbs

FOAM WEIGHT = 215,000 lbs

THE HOOP STRESS INCREASES FROM 1,200 PSI COMP. TO 515 PSI COMP. WHEN THE CONTENTS ARE ADDED TO THE SILO ($\therefore \Delta\sigma_1 = 1200 - 515 = 685$ PSI) (REF. #8 P. 33)

$$\therefore \frac{\text{WEIGHT OF K-65 RESIDUE}}{\Delta\sigma_1} = \frac{\text{WEIGHT OF DOME + FOAM}}{\Delta\sigma_2}$$

WHERE $\Delta\sigma_2$ IS THE CHANGE IN HOOP STRESS DUE TO ADDING THE WEIGHT OF THE FOAM AND THE DOME (DL+LL) TO THE K-65 RESIDUE.

WEIGHT OF THE FOAM AND THE DOME $\cong$ 555,000 lbs

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 9 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

VERTICAL WALL - CONT.

$\therefore \Delta\sigma_2 = \Delta\sigma_1$ (WEIGHT OF DOME + FOAM) / (WEIGHT OF RESIDUE)

$\Delta\sigma_2 = 685 (555{,}000) / (10{,}053{,}096)$

$\Delta\sigma_2 = 37.8$ PSI

$\therefore \sigma_{HOOP} = 1200 - 685 - 37.8$

$\sigma_{HOOP} = 477.2$ PSI COMP.

THIS IS BASED ON A WORST CASE ASSUMING THAT 76'Ø PORTION OF THE DOME COLAPSES ON THE FOAM. EVEN IN THIS WORST CASE, THE VERTICAL WALL IS STILL IN COMPRESSION. SINCE THE WALL IS IN COMPRESSION, THE WALL IS STABLE.

NOTE: THIS CALCULATION WAS MADE ASSUMING MOSTLY RIGID FOAM WAS APPLIED UNDER THE DOME. A DESIGN CHANGE WAS MADE IN WHICH RIGID FOAM WOULD BE APPLIED ONLY UNDER THE CENTER 36'Ø PORTION OF THE DOME. THEREFORE, SUPPORT WILL BE PROVIDED ONLY FOR THAT PORTION. THUS THE ABOVE CALCULATION IS CONSERVATIVE.

CALCULATION WORKSHEET

ORIGINATOR James Campbell C DATE 8-12-87 SHEET 10 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

BASE SLAB & EARTH BERM

A 2% INCREASE IN TOTAL CONTENT WEIGHT IS REALIZED DUE TO THE FOAM ADDITION. THEREFORE, NEITHER THE EARTH BERM NOR THE FOUNDATION WILL BE ADVERSELY EFFECTED BY THE ADDITION OF FOAM.

K-65 RESIDUE

THE FOAM SHOULD HAVE NO ADVERSE STRUCTURAL EFFECT ON THE K-65 RESIDUE PROVIDED THAT THE FOAM IS APPLIED UNIFORMLY DURING INSTALLATION.

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 11 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

ASSUMPTIONS :

1. THE DIMENSIONS ON THE K-65 SILO DRAWING (REF.#7) (PRELOAD DWG. # 517720-3) ARE ACCURATE AT 110°F. THEREFORE, "b_H" = 9'-4".

2. THE CONNECTION OF THE DOME TO THE WALL IS A FIXED CONNECTION.

3. THE DOME CAN BE APPROXIMATED AS A SPHERICAL SEGMENT.

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CALCULATION WORKSHEET

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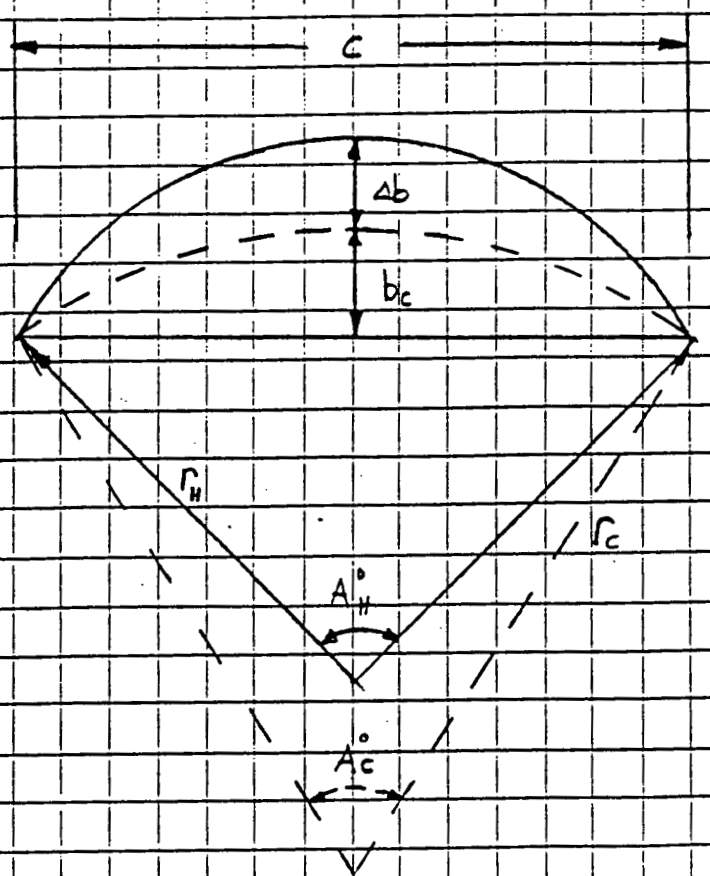
CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



GEOMETRY OF DOME EXPANSION / CONTRACTION

$b_H = b_c + \Delta b$

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 13 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

DEFINITION OF TERMS:

A° = THE ANGLE DEFINING A SPHERICAL SEGMENT (DEGREE)

A°_H = "A°" @ 120°F

A°_C = "A°" @ -20°F

a = ARC ON THE SPHERE (IN.)

a_H = "a" @ 120°F

a_C = "a" @ -20°F

b = RISE FROM THE TOP OF THE SILO WALL TO THE INSIDE SURFACE AT THE DOME APEX. (IN.)

b_H = "b" @ 120°F

b_C = "b" @ -20°F

Δb = CHANGE IN "b" DUE TO THERMAL CONTRACTION (IN)

HYP. = HYPOTENUSE OF AN INSCRIBED TRIANGLE (DEGREE)

r = RADIUS OF A THEORETICAL SPHERE. (IN.)

r_H = "r" @ 120°F

r_C = "r" @ -20°F

θ = ANGLE IN AN INSCRIBED TRIANGLE (DEGREE)

ε_c = COEFFICIENT OF LINEAR THERMAL EXPANSION FOR CONCRETE

C = SILO DIAMETER = 80 FT.

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 14 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

VERTICAL DOME MOVEMENT

$C = 960''$

$r_H = (4(b_H)^2 + c^2) / 8(b_H)$ (REF. #5 P.6-18)

$r_H = (4(112)^2 + (960)^2) / 8(112)$

$r_H = 1{,}084.5'' = 90.38'$

$C = 2(r_H) \sin(A_H^\circ/2)$ (REF. #5 P.6-118)

$\therefore \sin(A_H^\circ/2) = C/(2(r_H))$

$(A_H^\circ/2) = \sin^{-1}(C/(2(r_H)))$

$(A_H^\circ/2) = \sin^{-1}(960/(2)(1{,}084.5))$

$(A_H^\circ/2) = 26.268045$

$A_H^\circ = 52.536091^\circ$

$a_H = (\pi r_H A_H^\circ / 180^\circ)$ (REF. #5 P6-18)

$a_H = \pi(1{,}084.5)(52.536091)/180$

$a_H = 994.47363''$

$\varepsilon_c = 5.5 \times 10^{-6}$ in/in°F

$\Delta T = T_H - T_C = 120°F - (-20°F) = 140°F$

$\Delta a = a_H - a_c$

$a_c = a_H - (a_H)(\varepsilon_c)(\Delta T)$ (REF. #4 P.17)

$a_c = 994.47363 - (994.47363)(5.5 \times 10^{-6})(140)$

$a_c = 993.70789''$

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 15 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

AFTER CONTRACTION:

$a_c = 993.70789''$

$c = 960''$

$a_c = \pi (r_c)(A^\circ_c) / 180$ (REF. #5 P. 6-18)

$993.70789 = \pi (r_c)(A^\circ_c) / 180$

$(r_c)(A^\circ_c) = 56{,}935.268$ (EQ. #1)

$c = 2(r_c) \sin (A^\circ_c / 2)$ (REF #5 P.6-18)

$960 = 2(r_c) \sin (A^\circ_c / 2)$

$(r_c) \sin (A^\circ_c / 2) = 480$ (EQ. #2)

SOLVING EQ. #1 AND EQ. #2 SIMULTANEOUSLY

$r_c = 1{,}095.6795''$

$A^\circ_c = 51.963433^\circ$

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 16 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

$b_c = (c/2)\,TAN\,(A_H^\circ/4)$ (REF. #5 P. 6-18)

$b_c = (960/2)\,TAN\,(51.963433/4)$

$b_c = 480\,TAN\,(12.990858)$

$b_c = 110.73607''$

$\Delta b = b_H - b_c$

$\Delta b = 112'' - 110.73607''$

$\Delta b = 1.2639338''$

∴ THE MAXIMUM MOVEMENT OF THE UNINSULATED DOME IS ~ 1.264'' (FROM -20°F TO 120°F)

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 17 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

EXPOSED CONCRETE TEMP. - SUMMER

$q_r = \sigma A \varepsilon_1 (T_1^4 - T_2^4)$ (REF. #2 P. 12)

σ = Stefan - Boltzman constant = 0.1713×10^{-8} BTU/HR FT^2 °F

A = Area (ft^2) (assume 1 ft^2 for this calculation)

ε_1 = EMISSIVITY = 0.9

T_1 = CONCRETE TEMP (°R)

T_2 = AMBIENT TEMP. (°R)

q_r = SOLAR RADIATION INCIDENT UPON A HORIZONAL SURFACE

$q_r = (0.1713 \times 10^{-8})(1)(0.9)(T_1^4 - (120+460)^4)$

$q_r = 300$ BTU/HR FT^2 $\times$ 1 FT^2 = 300 BTU/HR (REF. #3 P. 341)

$\therefore T_1 = 745°R = 285°F$

$q_{convection} = h_o A \Delta t$ (REF. #2 P. 13)

h_o = SURFACE HEAT TRANSFER COEFFICIENT = 1.63 BTU/HR FT^2 °F

A = 1 ft^2

Δt = AVERAGE SURFACE TEMPERATURE - T_2

$q_{conv.} = (1.63)(1)(\frac{285+120}{2} - 120) \cong 135$ BTU/HR

$q_c = q_r - q_{conv} = 165$ BTU/HR

$\therefore 165 = (0.1713 \times 10^{-8})(1)(0.9)(T_1^4 - (580)^4)$

$T_1^* \cong 685°R \cong 225°F$

* THIS IS A SIMPLIFIED ESTIMATE OF CONCRETE TEMPERATURE. THE PURPOSE OF THIS CALCULATION IS TO SHOW THAT EXPOSED CONCRETE WILL EXCEED AMBIENT AIR TEMPERATURE (NOT TO PREDICT THE ACTUAL TEMP.)

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 18 OF 22

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

INSULATING THE DOME

THE TEMPERATURE OF UNINSULATED CONCRETE WILL EXCEED AMBIENT AIR TEMPERATURE DUE TO SOLAR RADIATION. THIS WILL PRODUCE A THERMAL CYCLIC STRESS ON THE DOME EVERY 24 HOURS AND ALMOST DOUBLE THE AMOUNT OF RISE ("b") IN THE DOME CALCULATED IN PREVIOUS CALCULATIONS.

ADVANTAGES TO INSULATING THE DOME

1. TO ELIMINATE TO SOLAR LOAD ON THE CONCRETE AND REDUCE "ΔT" IN THE CONCRETE.

2. REDUCE "ΔT" IN THE SUPPORTING FOAM.

3. WEATHER PROOF TO REDUCE DEGRADATION.

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 19 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

ASSUMPTIONS :

1. HEAT TRANSFER IS SIMPLIFIED TO CONDUCTANCE ONLY, BY ASSUMING THE RADIATION LOAD ON THE INSULATION IS EQUAL TO THE CONVECTION OFF OF THE INSULATION. THEREFORE, THE INSULATION SURFACE TEMPERATURE (T_o) IS EQUAL TO THE AMBIENT AIR TEMPERATURE (T_∞).

2. ALL FOAM BELOW GROUND LEVEL = GROUND TEMP.

3. THE CONCRETE TEMPERATURE AT THE DOME - SIDE WALL CONNECTION IS = GROUND TEMP.

4. NO ALLOWANCE IS MADE FOR THE INCREASE IN CONDUCTIVITY THAT THE STEEL ADDS TO THE CONCRETE.

5. NO ALLOWANCE IS MADE FOR VARIATION IN CONCRETE THICKNESS.

6. THE DOME TEMPERATURE CLOSE TO THE SIDEWALL IS NOT USED IN DETERMINING THE AVERAGE DOME TEMPERATURE.

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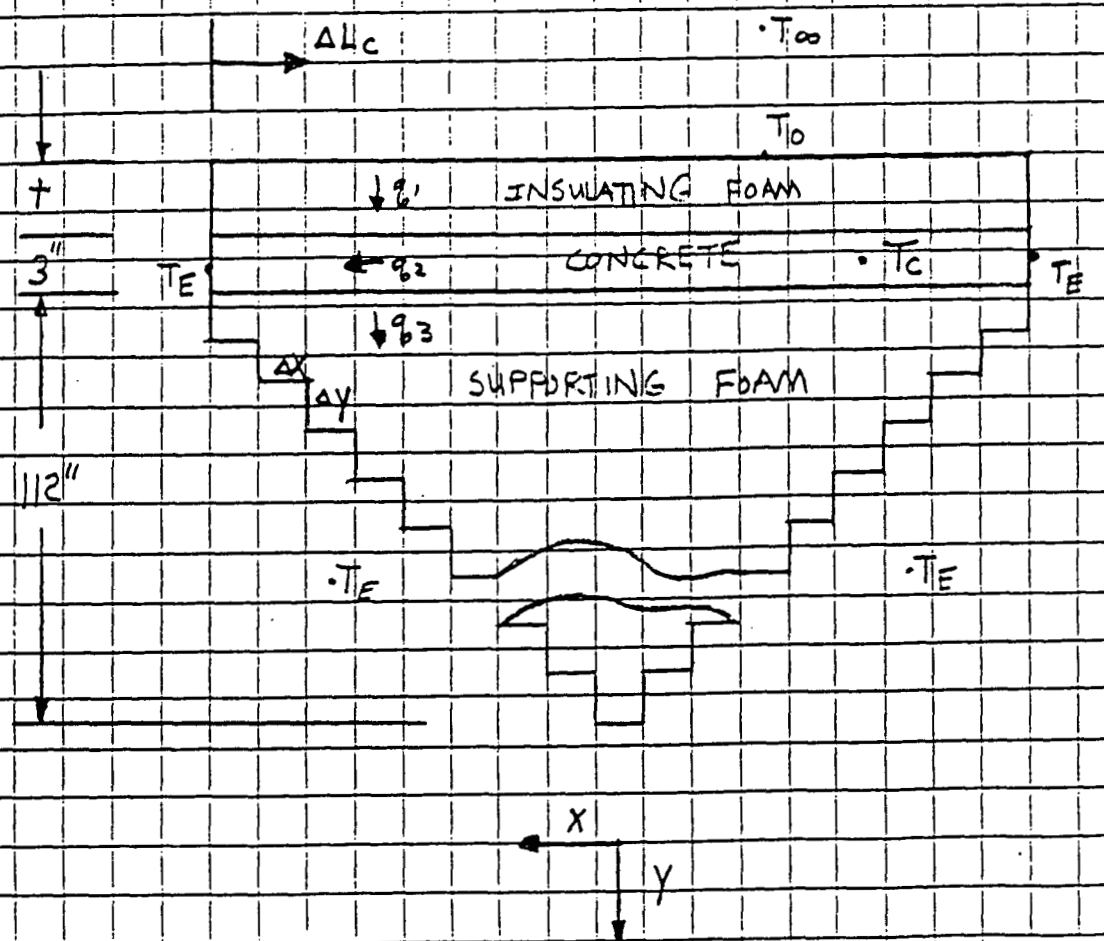
CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 20 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



HEAT TRANSFER SKETCH

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 21 OF 42

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PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

DEFINITION OF TERMS:

Δy = VERTICAL INCREMENT (IN.)
Δx = HORIZONAL INCREMENT (IN.)
q_c = CONDUCTION HEAT TRANSFER
q_1 = CONDUCTION THROUGH THE DOME INSULATION
q_2 = CONDUCTION THROUGH CONCRETE TO SIDEWALLS
q_3 = CONDUCTION THROUGH THE SUPPORT FOAM
A_{F1} = AREA FACTOR FOR "q_1"
A_{F2} = AREA FACTOR FOR "q_2"
A_{F3} = AREA FACTOR FOR "q_3"
C_{F1} = CONDUCTION FACTOR FOR "q_1"
C_{F2} = CONDUCTION FACTOR FOR "q_2"
C_{F3} = CONDUCTION FACTOR FOR "q_3"
ΔL_c = RADIAL DISTANCE FROM SIDEWALL INWARD (IN.)
t = THICKNESS OF FOAM INSULATION (IN.)
T_∞ = AMBIENT TEMPERATURE (°F) = 120°F
T_E = EARTH TEMPERATURE (°F) = 50°F
T_o = SURFACE TEMPERATURE (°F) = 120°F
T_c = CONCRETE TEMPERATURE (°F)

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CALCULATION WORKSHEET

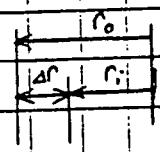
ORIGINATOR James Campbell DATE 8-12-87 SHEET 22 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

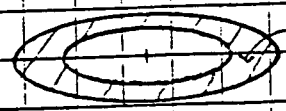
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

AREA FACTOR * (A_F)



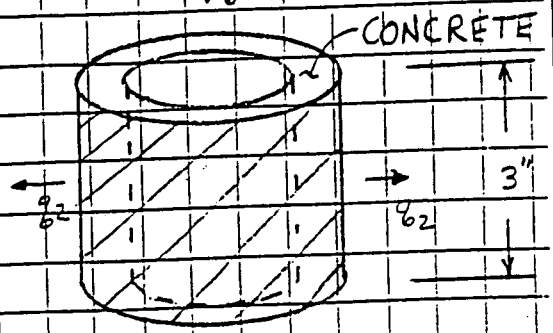
A_1 = AREA ⊥ TO q_1 (INSULATING FOAM)

$A_1 = \pi((r_o)^2 - (r_i)^2)$ (REF. #5 P. 6-22)



A_2 = AREA ⊥ TO q_2 (CONCRETE)

$A_2 = \pi\left(\frac{2(r_o) + 2(r_i)}{2}\right)(3'')$

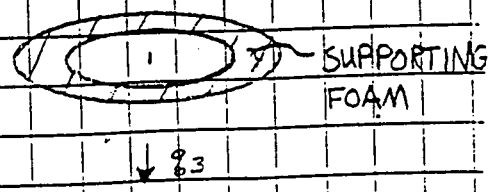


A_3 = AREA ⊥ TO q_3 (SUPPORTING FOAM)

$A_3 = \pi((r_o)^2 - (r_i)^2)$

$\therefore A_1 = A_3$

$A_1/A_2 = \pi((r_o)^2 - (r_i)^2) / \pi(r_o + r_i)(3)$



IF $r_o = 240''$ THEN $r_i = 240 - \Delta x = 235.7143''$

$A_1/A_2 = \pi((240)^2 - (235.7143)^2) / \pi(240 + 235.7143)(3)$

$A_1/A_2 \doteq 1.44$

$A_{F1} = A_1/A_2 \doteq 1.44$; $A_{F2} = A_2/A_2 = 1$; $A_{F3} = A_3/A_2 = A_1/A_2 = 1.44$

* THE AREA FACTOR GIVES A RATIO OF EACH CONDUCTANCE AREA RELATED TO THE CONCRETE AREA (SURFACE AREA OF A HOLLOW CYLINDER). IT IS PROVIDED SO THAT THE AREA OF EVERY SEGMENT IN THE DOME DOES NOT NEED TO BE CALCULATED. INSTEAD THE AREA FACTOR (RATIO OF AREAS) CAN BE USED FOR EVERY SEGMENT AS IT IS CONSTANT.

ADVANCED SCIENCES, INC.

CONDUCTANCE FACTOR (CF)

SINCE $q_c = A\left(\frac{k}{x}\right)(\Delta T)^*$, q_c VARIES DIRECTLY WITH AREA, THERMAL CONDUCTIVITY, AND TEMPERATURE AND INDIRECTLY WITH THICKNESS.

A CONDUCTANCE FACTOR (CF) CAN BE OBTAINED FOR EACH OF THE THREE CONDUCTIVE HEAT TRANSFER MEDIUMS BY SETTING $CF = (A_F)(T_d)(K)/t$. WHERE 't' IS THE THICKNESS OF EACH MEDIUM AT EACH GIVEN SEGMENT.

FOR INSULATING FOAM: t = INSULATION THICKNESS (t)

FOR CONCRETE: t = RADIAL DISTANCE FROM EACH GIVEN SEGMENT TO THE SIDEWALL (ΔL_d)

FOR SUPPORTING FOAM: t = VERTICAL DISTANCE FROM THE INSIDE SURFACE OF THE DOME TO GROUND LEVEL (RESIDUE) (Δy)

* REF. #3 P. 22

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 24 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

CONDUCTANCE FACTOR - CONT.

$\therefore C_{F1} = (A_{F1})(T_o)(K_1) / t$

$C_{F1} = (1.44)(120)(0.15) / t$

$C_{F1} = 25.92 / t$

$C_{F2} = (A_{F2})(T_F)(K_2) / \Delta L_c$

$C_{F2} = (1.)(50)(12.0) / \Delta L_c$

$C_{F2} = 600 / \Delta L_c$

$C_{F3} = (A_{F3})(T_F)(K_3) / \Delta y$

$C_{F3} = (1.44)(50)(0.15) / \Delta y$

$C_{F3} = 10.8 / \Delta y$

$\therefore T_c = ((C_{F1} * T_o) + ((C_{F3} + C_{F2}) \times T_F)) / (C_{F1} + C_{F2} + C_{F3})$

THE FOLLOWING TABLE SHOWS T_c AT VARIOUS INSULATION THICKNESSES (t).

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 25 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

T_c (CONCRETE TEMPERATURE)

		+ (INSULATION THICKNESS)					
		2"	4"	6"	12"	24"	36"
ΔL_c	Δy	T_c(°F)	T_c(°F)	T_c(°F)	T_c(°F)	T_c(°F)	T_c(°F)
48"	11.2"	83.4	72.7	67.0	59.7	55.2	53.6
96"	22.4"	96.1	84.3	77.4	67.0	59.7	56.8
144"	33.6"	102.0	91.4	84.3	72.7	63.6	59.7
192"	44.8"	105.6	96.1	89.3	77.4	67.0	62.3
240"	56.0"	108.0	99.5	93.1	81.2	70.0	64.8
288"	67.2"	109.7	102.0	96.1	84.3	72.7	67.0
336"	78.4"	111.0	104.0	98.4	87.0	75.2	69.1
384"	89.6"	112.0	105.6	100.4	89.3	77.4	71.0
432"	100.8"	112.8	106.9	102.0	91.4	79.3	72.7
480"	112.0"	113.4	108.0	103.4	93.1	81.2	74.4

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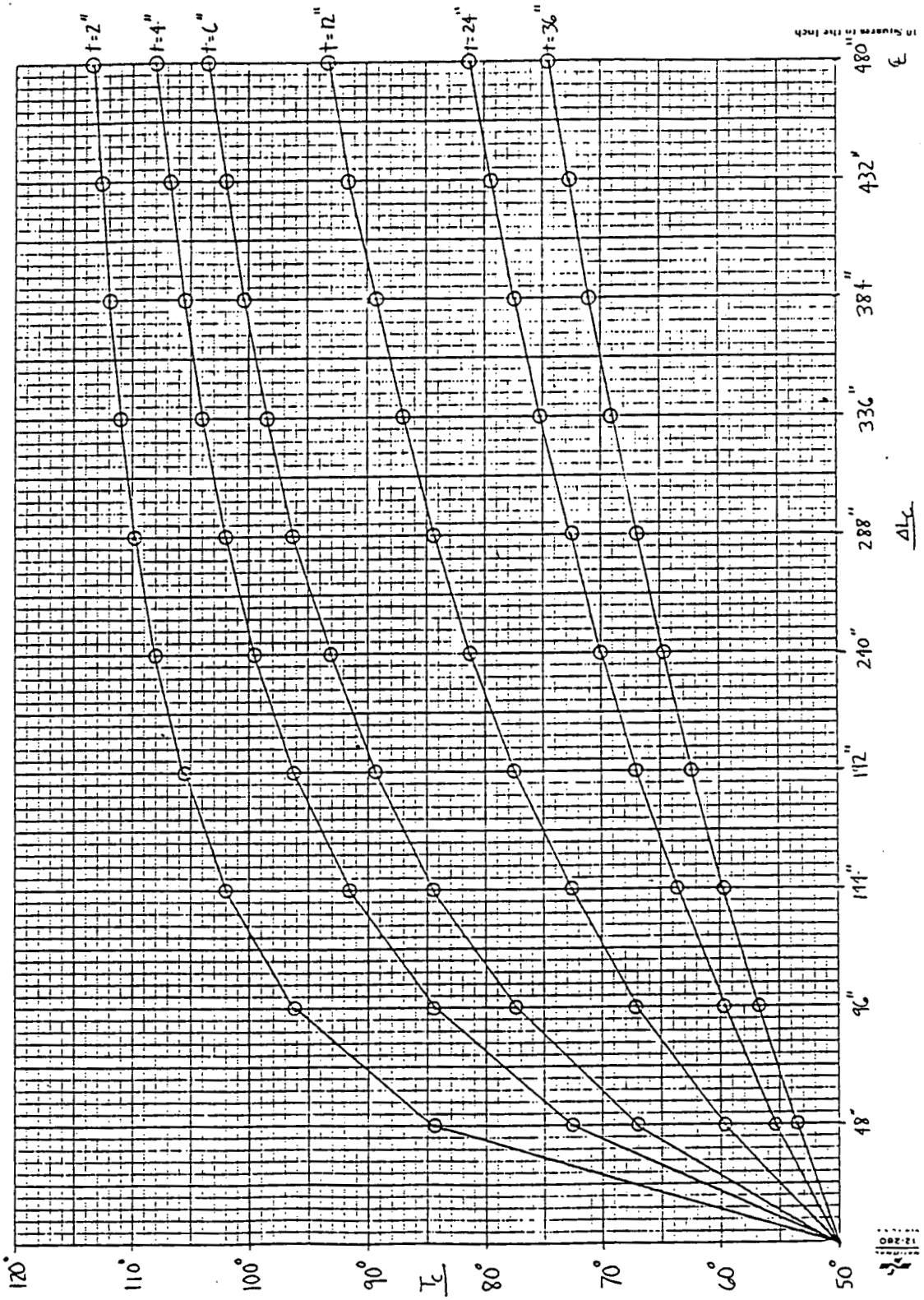
CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 26 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 27 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

AVERAGE DOME TEMPERATURES

W/ 2" OF INSULATION:

$T_c = (84.3 + 96.1 + 102.0 + 105.6 + 108.0 + 109.7 + 111.0 + 112.0 + 112.8 + (113.4)(1/2)) / (9\frac{1}{2})$

$T_c = 105.1°F$

SIMILARLY:

W/ 4" OF INSULATION $\Rightarrow T_c = 96.4°F$

W/ 6" OF INSULATION $\Rightarrow T_c = 90.5°F$

W/ 12" OF INSULATION $\Rightarrow T_c = 79.5°F$

W/ 24" OF INSULATION $\Rightarrow T_c = 69.5°F$

W/ 36" OF INSULATION $\Rightarrow T_c = 64.7°F$

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CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 28 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

MAXIMUM INSULATED DOME MOVEMENT

ASSUMING THAT THE RELATIONSHIP BETWEEN THE TEMPERATURE CHANGE (ΔT) AND THE VERTICAL DOME MOVEMENT (Δb) IS LINEAR, THE FOLLOWING VALUES ARE OBTAINED:

$$\Delta T = 140 - [(120 - T_c) \times 2]$$

AMOUNT OF INSULATION (+)	ΔT	VERTICAL MOVEMENT (Δb)
PREVIOUS CALC. 0"	120 - (-20) = 140°F	1.26"
2"	105.1 - (-5.1) = 110.2°F	0.99"
4"	96.4 - 3.6 = 92.8°F	0.84"
6"	90.5 - 9.5 = 81.0°F	0.73"
12"	79.5 - 20.5 = 59.0°F	0.53"
24"	69.5 - 30.5 = 39.0°F	0.35"
36"	64.7 - 35.3 = 29.4°F	0.26"

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 29 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

ASSUMPTION: ALL FOAM AT, AND BELOW GROUND LEVEL REMAINS AT A CONSTANT TEMPERATURE (EARTH TEMPERATURE).

∴ MAXIMUM DEPTH OF RIGID FOAM THAT WILL BE SUCEPTIBLE TO THERMAL EXPANSION/CONTRACTION IS 9⅓' (112")

W/2" OF INSULATION ⇒ MAXIMUM DOME TEMP. = 105.1°F
W/4" OF INSULATION ⇒ MAXIMUM DOME TEMP. = 96.4°F
W/6" OF INSULATION ⇒ MAXIMUM DOME TEMP. = 90.5°F

IF THE AVERAGE RIGID FOAM TEMPERATURE IS EQUAL TO THE AVERAGE OF THE DOME AND EARTH TEMPERATURE, THEN:

FOAM TEMP. W/2" INSULATION = (105.1 + 50)/2 = 77.55°F
ΔT = 77.55°F - 50°F = 27.55°F

FOAM TEMP. W/4" INSULATION = (96.4 + 50)/2 = 73.2°F
ΔT = 73.2 - 50 = 23.2°F

FOAM TEMP. W/6" INSULATION = (90.5 + 50)/2 = 70.25°F
ΔT = 70.25 - 50 = 20.25°F

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 30 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

∴ MAXIMUM LINEAR EXPANSION OF THE RIGID FOAM $= (\alpha)(L)(\Delta T)$*

WHERE : α = COEF. OF LINEAR EXPANSION = 3.5×10^{-5} in/in °F

L = 9⅓' (112")

ΔT = TEMPERATURE CHANGE (°F)

W/2" INSULATION : $(3.5 \times 10^{-5})(112)(27.55) = 0.108"$

W/4" INSULATION : $(3.5 \times 10^{-5})(112)(23.2) = 0.091"$

W/6" INSULATION : $(3.5 \times 10^{-5})(112)(20.25) = 0.079"$

W/12" INSULATION : $(3.5 \times 10^{-5})(112)(14.75) = 0.058"$

W/24" INSULATION : $(3.5 \times 10^{-5})(112)(9.75) = 0.038"$

W/36" INSULATION : $(3.5 \times 10^{-5})(112)(7.35) = 0.029"$

* REF. #4 P. 17

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 31 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

LOOKING AT THE EXPANSION / CONTRACTION CHARACTERISTICS OF THE CONCRETE DOME COMPARED TO THE RIGID SUPPORTING FOAM (SEE THE GRAPH ON PAGE 34), THE CONCRETE DOME EXHIBITS MUCH MORE MOVEMENT. THEREFORE, THE FORCE EXERTED ON THE CONCRETE BY THE FOAM WILL DECREASE IN THE SUMMER AND INCREASE IN THE WINTER. THE MAXIMUM ALLOWABLE FORCE MUST BE DETERMINED UNDER WINTER CONDITIONS.

IN DETERMINING THE MAXIMUM ALLOWABLE FORCE FOR THE CENTER PORTION OF THE DOME, THE MINIMUM THICKNESS OF FLEXIBLE FOAM DIRECTLY UNDERNEATH THE CENTER PORTION WILL BE DETERMINED.

(δ_{max}) MAX. DEFLECTION = CONTRACTION OF DOME − CONTRACTION OF FOAM

W/2" OF INSULATION: $\delta_{max} = \left(\frac{\Delta b}{2}\right) + 0.108 = \frac{0.99}{2} - 0.108 = 0.387''$

WORST CASE (FOAM INSTALLED UNDER SUMMER CONDITIONS)

$\delta_{max} = \Delta b - (2)(0.108) = 0.99 - (2)(.108) = \boxed{0.774''}$

NOTE: Δb IS BASED ON THE DOME MOVEMENT FROM −20°F TO 120°F. THE CONTRACTION OF THE FOAM IS BASED ON AN AMBIENT TEMPERATURE CHANGE OF 70°F. THEREFORE, THE FOAM CONTRACTION WOULD DOUBLE IF THE TEMPERATURE CHANGE WAS 140°F (120°F to −20°F).

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

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ORIGINATOR James Campbell DATE 8-12-87 SHEET 32 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

W/ 4" OF INSULATION:

WORST CASE: $\delta_{MAX} = \Delta b - (2)(0.091) = 0.84 - (2)(.091) = \boxed{0.658''}$

W/ 6" OF INSULATION:

WORST CASE: $\delta_{MAX} = \Delta b - (2)(0.077) = 0.73 - (2)(0.077) = \boxed{0.572''}$

NEGLECTING THE FORCE ABSORBED BY THE RIGID FOAM

$\delta = P\left(\frac{L}{E}\right)$ (REF #4 P.12)

P = PRESSURE ON THE CENTER PORTION OF THE DOME (psi)

L = DEPTH OF FLEXIBLE FOAM

E = MODULUS OF ELASTICITY OF THE FLEXIBLE FOAM (psi) = 3.6 psi

"E" WAS OBTAINED FROM MFR DATA (SEE PAGE 37), BY THE RELATIONSHIP

$1'' = (45\#/50in^2)(4''/E)$ @ 25% DEFLECTION $\Rightarrow E = 3.6$ psi

IF $P = P_{MAX} = 26$ psf (CAMARGO REPORT PAGE 31)

THEN:

W/2" OF INSULATION: $\delta = 0.774''$

$\delta = P\left(\frac{L}{E}\right) = \left(\frac{26}{144}\right)\left(\frac{L}{3.6}\right)$

$0.774 = \left(\frac{26}{144}\right)\left(\frac{L}{3.6}\right)$

$\Rightarrow L \cong 16''$ (MINIMUM ALLOWABLE DEPTH OF FLEX FOAM)

NOTE: THE DEFLECTION - PRESSURE RELATIONSHIP ESTABLISHED FOR THE FLEXIBLE FOAM IS ASSUMED LINEAR BASED UPON A TELECON WITH THE FOAM MANUFACTURER (SEE PAGE 36)

ADVANCED SCIENCES, INC

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 33 OF 42.
CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]
PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

SIMILARLY:

W/ 4" OF INSULATION : $\delta = 0.658''$

$\delta = P\left(\frac{L}{E}\right)$ (REF #4 P.12)

$0.658 = \left(\frac{26}{144}\right)\left(\frac{L}{2.6}\right)$

$\Rightarrow L \cong 13''$

W/ 6" OF INSULATION : $\delta = 0.572''$

$\delta = P\left(\frac{L}{E}\right)$ (REF #4 P.12)

$0.572 = \left(\frac{26}{144}\right)\left(\frac{L}{2.6}\right)$

$\Rightarrow L \cong 12''$

THEREFORE, THE MINIMUM THICKNESS OF FLEXIBLE FOAM RANGES FROM 12" TO 16". INCREASING THIS MINIMUM BY 100% (24" TO 32"), WHILE SLIGHTLY REDUCING THE SUPPORT THE FOAM GIVES TO THE DOME, WILL REDUCE THE CONCERN RELATING TO THE UNCERTAIN BEHAVIOR OF THE RIGID FOAM DURING THE EARLY STAGES OF CURING (~4 weeks).

ADVANCED SCIENCES, INC.

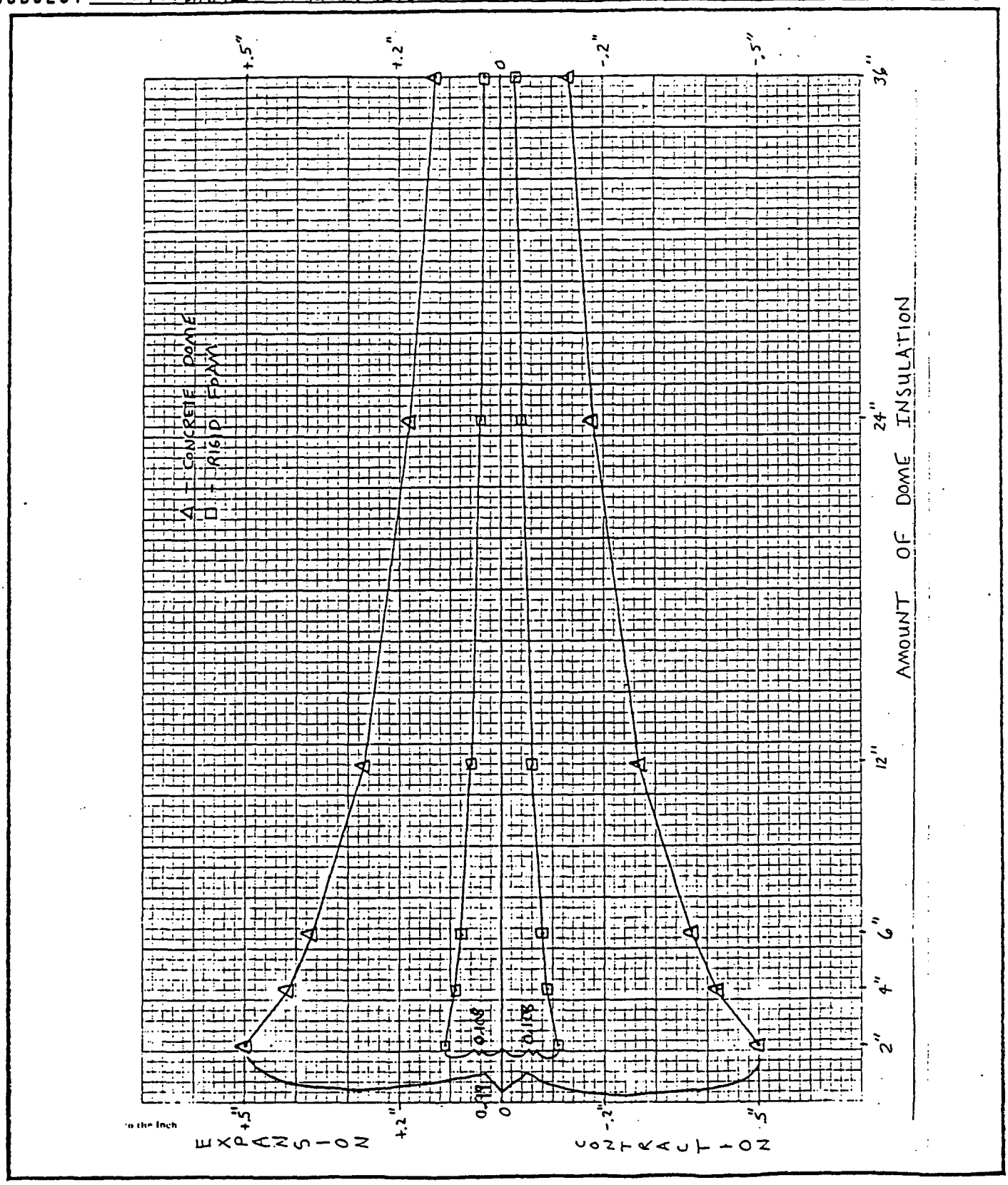
CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 34 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME



ADVANCED SCIENCES, INC

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 35 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

SUPPORT FOAM DISCUSSION

THE COMPRESSION MODULUS OF THE RIGID FOAM IS 24 PSI. THEREFORE, THE RIGID FOAM CAN CARRY THE DEAD WEIGHT LOAD (DL) OF THE CENTER 20'Ø PORTION OF THE DOME PLUS THE 20 PSF LIVE LOAD (LL).

THUS, THE DESIGN CAN SUSTAIN THE WEIGHT OF THE CENTER 20'Ø PORTION OF THE DOME PLUS THE 20 PSF LIVE LOAD. HOWEVER, NO SUPPORT IS PROVIDED FOR THE REMAINING PORTION OF THE DOME.

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

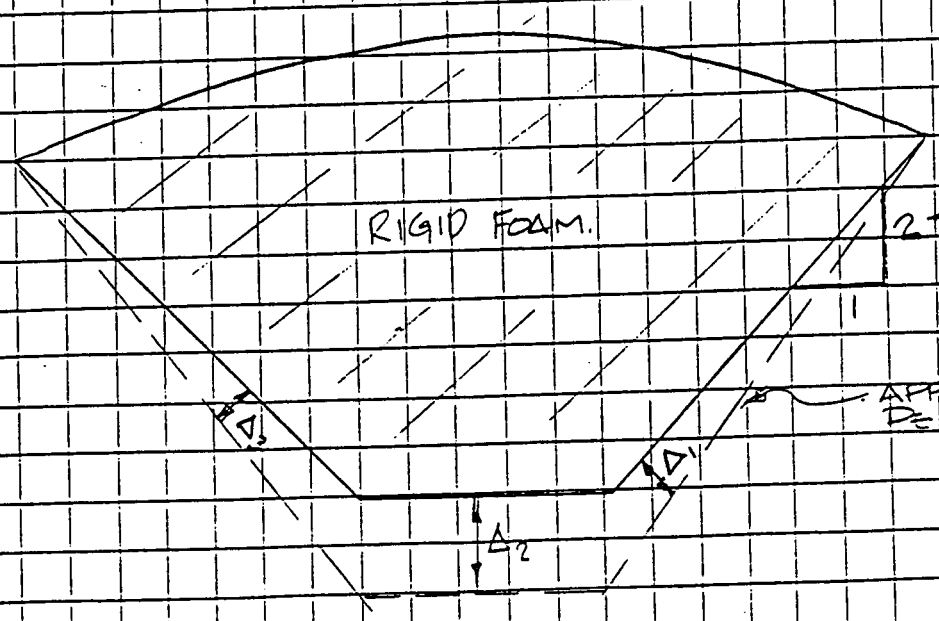
ORIGINATOR [illegible] DATE 8-20-87 SHEET [illegible] OF [illegible]

CALC.NO. 60295-01 REV.NO. 0 DATE 8/20/87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

THE PURPOSE OF THE FOLLOWING CALCULATION IS TO DEMONSTRATE A RELATIONSHIP BETWEEN % VOLUME CHANGE OF FOAM DURING CURING AND THE RESULTING DEFLECTION OF A FLEXIBLE FOAM LAYER OF A CERTAIN THICKNESS. THE LOAD APPLIED TO THE DOME IS A RESULT OF THIS DEFLECTION OF FLEXIBLE FOAM



ASSUMPTIONS – • FLEXIBLE FOAM OBEYS HOOKE'S LAW

$E_{(FLEXIBLE\ FOAM)} = \frac{45^{\#}}{\text{POUND}} = .9\ \text{PSI} = 129.6\ \text{PSF}$ (PG)

• 2:1 SLOPE

HEIGHT OF CONTENTS = 20' (SILO WITH LARGEST VOID VOL. (SILO #1))

TOTAL HEIGHT OF SILO FROM GROUND LEVEL TO DOME TOP

= 26'-8" + 9'-4" = 36'

36
− 20 – CONTENTS
− 2'-2" – LAYER OF RIGID FOAM.
11'-10" ≈ 12'-0" ← MAX HEIGHT FOR CALCULATING EXP.

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 8·10·87 SHEET 37 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8/21/87 CHECKED [illegible]

PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

THE RIGID FOAM IS MODELED AS CONCENTRIC VOLUMES. THE VOLUMETRIC INCREASE IS CALCULATED DUE TO FOAM EXPANSION. THE INCREASE IN HEIGHT (h) IS CALCULATED BY THE FOLLOWING RELATIONSHIPS.

EQN 1.- VOLUME FOR SOLID CYLINDER $V = \frac{\pi}{4} d^2 h$ d - DIAMETER OF CYLIN.

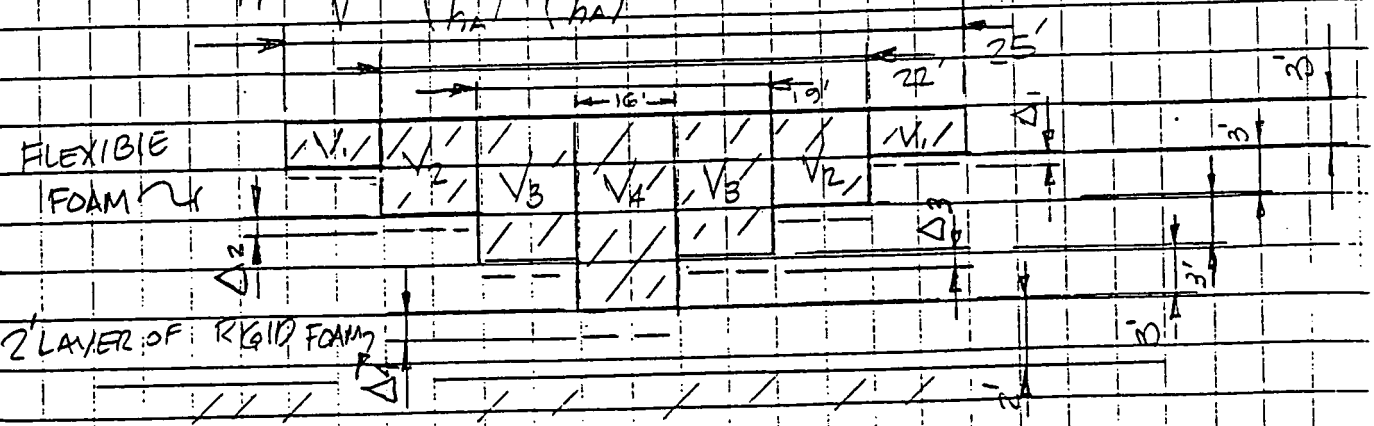
EQN 2.- VOLUME FOR HOLLOW CYLINDER $V = \frac{\pi}{4}(d_o^2 - d_i^2)h$ d_o - OUTSIDE DIA, d_i - INSIDE DIA.

USING THE RELATIONSHIP $d = \frac{d_A}{h_A} h$ SUBSTITUTE IT INTO EQN 1. h CAN BE SOLVED FOR WHEN SET EQUAL TO THE EXPANDED VOLUME (V_E). d_A = ORIGINAL DIAMETER h_A = ORIGINAL HEIGHT.

$$V_E = \frac{\pi}{4}\left(\frac{d_A}{h_A} h\right)^2 h \Rightarrow h = \sqrt[3]{\frac{V_E\,(4)}{\pi\,(d_A/h_A)^2}} \quad \text{EQN (3)}$$

SIMILIARLY, FOR EQN 2.

$$h = \sqrt[3]{\frac{V_E\,(4)}{\pi\left(\frac{d_o}{h_A}\right)^2 \pi\left(\frac{d_i}{h_A}\right)^2}} \quad \text{EQN (4)}$$



CROSS SECTION VIEW OF RIGID FOAM MODEL

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

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ORIGINATOR [illegible] DATE 8-20-87 SHEET 38 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8/21/87 CHECKED [illegible]

PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

NEXT CALCULATE Δ

Δ = h (EXPANDED VOLUME) − h (ORIGINAL VOLUME)

$\frac{\Delta}{X}$ = % DEFLECTION OF THE FLEXIBLE FOAM.
WHERE X = THE DISTANCE FROM VOLUME ELEMENT TO THE LOWER RIGID FOAM LAYER (FT).

THE LOAD (PSF) IS CALCULATED FROM THE FOLLOWING RELATIONSHIP

$\frac{\%\ \text{DEFL.}}{25\%} \times 129.6$ = LOAD (PSF) (EQN 5)

THE TOTAL LOAD (LBS) PRODUCED BY THE EXPANDED VOLUME ELEMENT = LOAD (PSF) × AREA (FT^2) = LOAD (LBS)

EXAMPLE: FOR VOLUME #1

$A = \pi/4\,(25^2 - 22^2) = 110.7\ ft^2$ $V = Ah = 110.7(3) = 332.2\ ft^3$

$V \times 1.06 = 352.2$ $h = \sqrt[3]{\frac{(352.16)(4)}{\pi\left[(25/3)^2 - (22/3)^2\right]}} = 3.058' \doteq 3.06'$

$\Delta = .06$ $X = 3(3) + 2 = 11'$ $\frac{\Delta}{X} = .0055$

LOAD (PSF) = $\frac{.0055}{.25}(129.6) = 2.85$ PSF

LOAD (lbs) = 110.7 (2.85) = 315.6# ≈ 316#.

VALUES ARE TABULATED ON THE FOLLOWING PG.

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

ORIGINATOR [illegible] DATE 8-20-87 SHEET 39 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8/21/87 CHECKED [illegible]

PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

VOL. #	SURFACE AREA ($\pi/4\ d^2$) OR $\pi/4(d_o^2-d_i^2)$ (ft^2)	VOLUME SUR. AREA x h. (ft^3)	VOLUME x 1.06 (ft^3)	NEW h (FT)	Δ (FT)	x (FT)	LOAD (PSF)	LOAD (lbs)
1	110.7	332.2 (h=3)	352.2	3.06	.06	11	2.85	516
2	96.6	579.6 (h=6)	614.4	6.12	.12	8	7.78	751.2
3	82.5	742.5 (h=9)	787.1	9.18	.18	5	18.66	1539.6
4	201.1	2413.2 (h=12)	2558	12.23	.23	2	59.6	11988.8
Σ	490.9	Σ 4067.3						Σ 14595.6

THE AVERAGE LOAD ON THE DOME IN lbs = 14595.6.
(DUE TO FOAM EXPANSION)

THE AVERAGE LOAD ON THE DOME IN PSF =
(DUE TO FOAM EXPANSION)

$$\frac{14595.6}{490.9} = 29.7 \text{ PSF} \simeq 30 \text{ PSF}$$

ADVANCED SCIENCES, INC.

CALCULATION WORKSHEET

5976

ORIGINATOR [illegible] DATE 8-20-87 SHEET 40 OF 42

CALC.NO. 60295-01 REV.NO. 0 DATE 8/21/87 CHECKED [illegible]

PROJECT FMPC FERNALD OHIO K-65 INVESTIGATION JOB NO.

SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

AS THE RIGID FOAM FILLS THE OPEN AREA LEFT IN THE FLEXIBLE FOAM LAYER, THE WEIGHT COMPRESSES THE FLEXIBLE FOAM BY THE AMOUNT CALCULATED BELOW.

WT OF RIGID FOAM = 2 PCF

VOL. ELEMENT #	WEIGHT (lbs)	SURFACE AREA $(ft)^2$	LOAD (PSF) $\left(\frac{WT}{AREA}\right)$
1	(2)(332.2) = 664.4	110.7	6
2	(2)(579.6) = 1159.2	96.6	12
3	(2)(742.5) = 1485	82.5	18
4	2(2413.2) = 4826.4	201.1	24
			Σ 60.0

AVG. LOAD = 60/4 = 15 PSF AVG LOAD DUE TO DEAD WT.

AVG DEFLECTION DUE TO DEAD WT. (USE EQN 6)

% DEFL / 25% × 129.6 = LOAD (PSF) ⇒ SUBSTITUTING 15 PSF FOR LOAD

AVG % DEFL. = $\frac{15}{129.6}$ (25) = 3%.

SIMILARLY CALCULATE % DEFL. FOR EXPANSION –

AVG % DEFL (DUE TO EXPANSION) = $\frac{50}{129.6}$ (25) = 6%.

THE SUM OF THESE DEFLECTIONS = 9% < 25%.

∴ THE ASSUMPTION OF HOOKE'S LAW IS VALID.

ADVANCED SCIENCES, INC.

APPENDIX #1

ADVANCED SCIENCES, INC.

RECORD OF TELECON

PROJECT: FERNALD FMPC RI/FS CONTRACT: DE-AC05-86OR-21659

FROM D.R. SMITH / J. CAMPBELL OF ASI	FILE	DATE 8/10/87
TO DAVE DRESSEL OF FOAM ENTERPRISES, INC.	JOB NO.	TIME 11:00 AM.

ITEMS OF DISCUSSION	ACTION REQ'D. (INCLUDE NAMES & DATES)
1. BEHAVIOR OF FLEXIBLE FOAM. QUESTION. ASKED BY DRS/JC. CAN IT BE ASSUMED THAT THE COMPRESSIVE PRESSURE ON THE FLEXIBLE FOAM AND THE RESULTING DEFLECTION EXHIBIT A LINEAR RELATIONSHIP IN THE RANGE OF 0 TO 25% DEFLECTION (IE. OBEYS HOOKE'S LAW)? ANSWER. YES. QUESTION ASKED BY DRS/JC. WHAT CHANGES OCCUR IN THE FLEXIBLE FOAM DURING CURING? ANSWER SINCE THE FLEXIBLE FOAM IS OPEN CELL, THE FOLLOWING FACTS APPLY: 1). THE INTERNAL GASES ARE QUICKLY DISSIPATED. 2). NO PERMANENT VOLUME CHANGE OCCURS DURING CURING. 3). THE HEAT GENERATED DURING CURING IS QUICKLY DISSIPATED. 4). THE TEMPERATURE EFFECTS ON THE FLEXIBLE FOAM (THERMAL EXPANSION / CONTRACTION) CAN BE NEGLECTED.	NONE REQ'D. TELECON INITIATED FOR INFORMATIONAL PURPOSES.

DISTRIBUTION:

DAVE DRESSEL

CALCULATION WORKSHEET

ORIGINATOR James Campbell DATE 8-12-87 SHEET 42 OF 42
CALC.NO. 60295-01 REV.NO. 0 DATE 8-13-87 CHECKED [illegible]
PROJECT FMPC, FERNALD OHIO K-65 INVESTIGATION JOB NO. 60295
SUBJECT STRUCTURAL EVALUATION OF FOAM SUPPORT FOR K-65 SILO DOME

APPENDIX #2

FOAM ENTERPRISES

13630 Watertower Circle
Minneapolis, MN 55441
(612) 559-3266
(800) 328-3342

1703 Crosspoint
Houston, Texas 77054
(713) 796-9743

CHEMICAL SYSTEM UPC 281

DESCRIPTION: INTEGRAL SKIN FLEXIBLE FOAM

UPC-281 is a MDI based, two component chemical system. This medium low density, open-celled foam has excellent and tough integral skin when cast in metal or plastic molds. It exhibits excellent energy absorption properties over a wide temperature range from 0°F to 150°F. This moderately firm foam is used to package very expensive objects, where flexible cushioning characteristics are needed to dampen shock and resonant frequency encountered in most shipping. It is also recommended for molding arm or head rests for use in furniture, aircraft or automobiles.

CHEMICAL PROPERTIES: (@ 77°F)

Viscosity, CPS	
A-Component: 100	B-Component: 500-600
Specific Gravity	
A-Component: 1.23	B-Component: 1.10
Reactivity Profile	
Cream time, sec.	15-18
Rise time, sec.	30-35
Tack free, sec.	35-40
Mixing Ratio (By Weight) A/B	25/75
Processing Temperature, °F	75-80
Mold Temperature, °F	80-90
Demold Time, min.	10

PHYSICAL PROPERTIES:

Core Density (Free Rise) LB/Ft^3	4
Tensile Strength, PSI	15
Tear Strength, PLI	1.2
Elongation, %	110-120
Resiliency, % ball rebound	60-64
4" ILD, LBS/50 in^2 (based on 4" free rise foam)	
25% Deflection	45 (core)
65% Deflection	98 (core)
Air Flow	3.2

000139

ADVANCED SCIENCES, INC

APPENDIX B

5976

FOAM ENTERPRISES, INC.

13630 Watertower Circle
Minneapolis, MN 55441
(612) 559-3266
(800) 328-3342

MG2-B

RIGID URETHANE BARGE FOAM

INDUSTRIAL FLOTATION

DESCRIPTION:

MG-2.0-B is formulated for use in industrial (barge) flotation applications with large "froth/pour" equipment.

The foam exhibits below normal exothermic heat generation during the "froth/pour" (using R-12) operation and has excellent flowing characteristics.

PROCESSING CHEMICAL PROPERTIES:

	Test Temp. °F.	ASTM Meth.	Test Unit	"A" Component	"B" Component
Viscosity	77°F.	D-1638	cps	250-350	900-1000
Specific Gravity	77°F.	D-1638	gr/cc	1.24	1.21
Ratio (Parts by Weight)				50	50
Cream Time (no R-12)	77°F.			25-30 seconds	
Rise Time				2 minutes, 50 second	
Tack Free Time				3 minutes, 15 second	
Density (no R-12)	77°F.		lbs/ft^2	2.0 ± 0.1	

FOAM PHYSICAL PROPERTIES:

Nominal Density	77°F.	D-1622	lbs/ft^3 (with R-12)	1.8 ± 0.1
k-Factor(BTU/ft^2-hr-°F/inch)		D-177		0.15 aged
Compressive strength	77°F.	D-1621	psi(10% deflection)	24.0
Closed cell percent		D-1940	o/o	92
Water Absorption	74°F.	D-2127	lbs/ft^2	0.1
Dimensional Stability		D-2126	(% volume change)	
4 Weeks	158°F.	at	100% RH	+ 16
3 Weeks	158°F.	at	100% RH	+ 16
2 Weeks	158°F.	at	100% RH	+ 14
1 Week	158°F.	at	100% RH	+ 12
4 weeks	-30°F.			-1.5
24 hours	30°F.		Dry cold	no change

Shelf-life 6 months from manufacturing date

000141 (See reverse side)

5976

FOAM ENTERPRISES

13630 Watertower Circle
Minneapolis, MN 55441
(612) 559-3266
(800) 328-3342

1703 Crosspoint
Houston, Texas 77054
(713) 796-9743

CHEMICAL SYSTEM UPC 281

DESCRIPTION: INTEGRAL SKIN FLEXIBLE FOAM

UPC-281 is a MDI based, two component chemical system. This medium low density, open-celled foam has excellent and tough integral skin when cast in metal or plastic molds. It exhibits excellent energy absorption properties over a wide temperature range from 0°F to 150°F. This moderately firm foam is used to package very expensive objects, where flexible cushioning characteristics are needed to dampen shock and resonant frequency encountered in most shipping. It is also recommended for molding arm or head rests for use in furniture, aircraft or automobiles.

CHEMICAL PROPERTIES: (@ 77°F)

Viscosity, CPS	
A-Component: 100	B-Component: 500-600
Specific Gravity	
A-Component: 1.23	B-Component: 1.10
Reactivity Profile	
Cream time, sec.	15-18
Rise time, sec.	30-35
Tack free, sec.	35-40
Mixing Ratio (By Weight) A/B	25/75
Processing Temperature, °F	75-80
Mold Temperature, °F	80-90
Demold Time, min.	10

PHYSICAL PROPERTIES:

Core Density (Free Rise) LB/Ft^3	4
Tensile Strength, PSI	15
Tear Strength, PLI	1.2
Elongation, %	110-120
Resiliency, % ball rebound	60-64
4" ILD, LBS/50 in^2 (based on 4" free rise foam)	
25% Deflection	45 (core)
65% Deflection	98 (core)
Air Flow	3.2

000142

Attachment 5

5976

TRIP/TELEPHONE REPORT

TELEPHONE /X/ DATE: April 22, 1988

VISIT /_/ LOCATION: Knoxville, Tennessee

FROM: David Porter PROJ. NO. 303317

NAME/TITLE: Keith Plowman, Research Leader TELE. NO. 409/238-7722

NAME/TITLE: DEPT: R&D

ORGANIZATION: Dow Urethanes R&D

ADDRESS: Freeport, Texas

SUBJECT: Heat of Reaction of Urethanes

COMMENTS:

Reaction of isocyanates with polyols to produce polyurethane is 24Kcal/mole and does not vary much with type.

Blowing agent will affect overall heat build-up due to vaporization.

ACTION:

5976

6.0

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Table 2. Physical Properties of Commercial Rigid Foamed Plastics

Property	ASTM test	Cellulose acetate	Epoxy		Phenolic		Extruded plank	
density, kg/m³[a]		96–128	32–48	80–128	32–64	112–160	35	53
mechanical properties								
compressive strength, kPa[b] at 10%	D 1621	862	138–172	414–620	138–620		310	862
tensile strength, kPa[b]	D 1623	1,172		345–1,240	138–379		517	
flexural strength, kPa[b]	D 790	1,014		1,380–5,516	172–448		1,138	
shear strength, kPa[b]	C 273	965			103–207		241	
compression modulus, MPa[c]	D 1621	38–90	3.9	14.5–44.8			10.3	
flexural modulus, MPa[c]	C 790	38		17.2–41.4			41	
shear modulus, MPa[c]	C 273				2.8–4.8		10.3	
thermal properties								
thermal conductivity, W/(m·K)[c]	C 177	0.045–0.046	0.016–0.022	0.035–0.040	0.029–0.032	0.035–0.040	0.030	
coefficient of linear expansion, 10^{-5}/°C	D 696		1.5	4.1	0.9	4.5	6.3	6.3
max service temperature, °C		177	205–260	205–260	132	205	74	
specific heat, kJ/(kg·K)[d]	C 351						1.1	
electrical properties								
dielectric constant	D 1673	1.12			1.19–1.20	1.19–1.20	<1.05	<1.05
dissipation factor		20			0.028–0.031	0.028–0.031	<0.0004	<0.0004
moisture resistance								
water absorption, vol %	C 272	4.5			13–51	10–15	0.02	0.05
moisture vapor transmission, g/(m·s·GPa)[e]	C 355		58				35	
references		21	129	129	130–131	130–131	21, 133	21

[a] To convert kg/m³ to lb/ft³, multiply by 0.0624.
[b] To convert kPa to psi, divide by 6.895.
[c] To convert MPa to psi, multiply by 145.
[d] To convert kJ/(kg·K) to Btu/(lb·°F), divide by 4.184.
[e] To convert GPa to psi, multiply by 145.000.

Table 2 (*continued*)

Polystyrene					Poly(vinyl chloride)		Polyurethane						Urea formaldehyde
										Isocyanurate			
Expanded plank			Extruded sheet				Polyether			Bun	Laminate		
16	32	80	96	160	32	64	32–48	64–128	144–192	304–400	32	32	13–19
90–124	207–276	586–896	290	469	345	1,035	138–344	482–1,896	2,000–3,800	8,270–13,800	117–206	97–282	34
145–193	310–379	1,020–1,186	2,070–3,450	4,137–6,900	551	1,207	138–482	620–2,000	1,585–3,100	4,800–8,960	248–290		
193–241	379–517				586	1,620	413–689	1,380–2,400		4,825–13,800			
	241				241	793	138–207	413–896		52,400	117		
	3.4–14				13.1	35	2.0–4.1	10.3–31					
	9.0–26				10.3	36	5.5–6.2	5.5–10.3					
	7.6–11.0				6.2	21	1.2–1.4	3.4–10.3			1.7		
0.037	0.035	0.035	0.035	0.035	0.023		0.016–0.025	0.022–0.030	0.027–0.036	0.049–0.060	0.019	0.020	0.026–0.030
5.4–7.2	5.4–7.2	5.4–7.2					5.4–7.2	7.2	7.2	7.2			
74–80	74–80	74–80	77–80	80			93–121	121–149	121–149	121–149	149	149	
							ca 0.9	ca 0.9	ca 0.9	ca 0.9			
1.02	1.02	1.02	1.27	1.28			1.05	1.1	1.2	1.4			
0.0007	0.0007	0.0007	0.00011	0.00014			13	18	32				
1–4	1–4	1–4											
<120	35–120	23–35	86	58	15		35–230	50–120	12		230		1,610–2,000
	131–132	134			135	135	136	136	136	136	137	137	138

Table 3. Physical Properties of Commercial Flexible Foamed Plastics

Property	ASTM test	Expanded acrylonitrile–butadiene rubber	Expanded butyl rubber		Expanded natural rubber		Expanded neoprene		Expanded SBR	Latex	Foam	Rubber
density, kg/m³[a]		160–400	125–144	224–304	56	320	112	192	72	80	130	160
cell structure		closed	closed	closed	closed	closed	closed	closed	closed	open	open	open
compressive strength												
10% deflection, kPa[b]	D 1621											
25% deflection, kPa[b]	D 1621		11–13.8	25–38				52				
tensile strength, kPa[b]	D 1564	275				206		758	551	103		
tensile elongation, %	D 1564							500		310		
rebound resilience, %	D 1054		39–56	30–16						73		
tear strength, (N/m)[c] × 10^2	D 624											
max service temperature, °C		100			70	70	105	70	70			
thermal conductivity, W/(m·K)	C 177	0.036–0.043			0.036	0.043	0.040	0.065	0.030		0.050	
electrical properties refs.											3	3
cushioning properties ref.												
mechanical properties refs.		128		128		128		128	128	128	128	128

[a] To convert kg/m³ to lb/ft³, multiply by 0.0624.
[b] To convert kPa to psi, divide by 6.895.
[c] To convert N/m to lbf/in., divide by 1.75.

Table 3 (*continued*)

Polyethylene sheet						Polypropylene			Polyurethane									
Polyethylene extruded plank				Extruded	Cross-linked	Unmodified	Modified	Sheet	Supersoft		Polyether slab		Poly(vinyl chloride)			Silicone Liquid	Silicone Sheet	Silicone Sheet
35	64	96	144	43	26–38	64–96	64–96	10	24	18	29	38	56	112	96	272	160	400–544
closed	closed	closed	closed	closed	closed	closed	closed		open	open	open	open	closed	closed	open	open	open	closed
48	75	124	360			550	206	4.8										
138	241	413	690	41		830	344		2.2	1.9	5.0	7	10.3	24	3.4	36 at 20%		
60	60	60	60	276	276–480	1100	1380	138–275	82	62	140	115			220	227	310	550–700
				50		25	75		190	220	258	163						
									31		49	55						
10.5	17.5	26	51	26							6	3						
82	82	82	82	82	79–93	135	135	121			125					350	260	232
0.053	0.058	0.058	0.058	0.040–0.049	0.036–0.040	0.039	0.039	0.039			0.040		0.035	0.040		0.078	0.086	
140	140	140	140	21, 140				131	141	43	43,	43	143	143		144	131	131
				140							142							
140	140	140	140	140	131	145	145	131	128	128	128	128	128	128	128	144	131	131