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DOE/NV/00597-6

Advanced Energy Systems Division

Spent Fuel Dry Storage Technology Development: REPORT OF CONSOLIDATED THERMAL DATA

SEPTEMBER 1980

Prepared For
THE UNITED STATES DEPARTMENT OF ENERGY
Contract No. DE-AC08-76NVOO597

Westinghouse Electric Corporation
Advanced Energy Systems Division
P.O. Box 10864
Pittsburgh, Pennsylvania 15236

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Printed in the United States of America

Available from:

National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price: Printed Copy $6.50
Microfiche $3.50

DOE/NV/00597-6
UC-85

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ABSTRACT

Experiments are underway at the Nevada Test Site, E-MAD Facility as part of an effort to develop methods for the dry storage of PWR and BWR spent fuel assemblies. The results of thermal tests performed to date are reviewed. They indicate that PWR fuel with decay heat levels in excess of 2 kW could be stored in isolated drywells in Nevada Test Site soil without exceeding the current fuel clad temperature limit (715°F).

The document also assesses the ability to thermally analyze near-surface drywells and above-ground storage casks and it identifies analysis development areas. It is concluded that the required analysis procedures, computer programs, etc., are already developed and available. Analysis uncertainties, however, still exist but they lie mainly in the numerical input area. Soil thermal conductivity is of primary importance in analysis and is a parameter that requires additional study to better understand the soil drying mechanism and the effects of moisture.

Work is also required to develop an internal canister subchannel model using one of the available computer programs designed for that purpose. In addition, the ability of the overall drywell thermal model to accommodate thermal interaction effects between adjacent drywells should be confirmed. In the experimental area, tests with two BWR spent fuel assemblies encapsulated in a single canister should be performed to establish the fuel clad and canister temperature relationship. This is needed to supplement similar experimental work which has already been completed with PWR fuel.

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1.0 INTRODUCTION AND PURPOSE

The Spent Fuel Handling and Packaging Program (SFHPP) was initiated in 1977 by the U. S. Department of Energy. As part of that program, the Westinghouse Advanced Energy Systems Division has been involved in the design of methods for the dry storage of spent commercial reactor fuel and this work is accompanied by a series of supportive experiments at the Nevada Test Site, E-MAD Facility. A detailed description of experiment hardware and E-MAD fuel handling and storage capabilities is presented in Reference 1. The systems currently under development are intended for the interim (30-50 year periods) storage of intact spent fuel assemblies. However, it is fully expected that the technology and concepts resulting from the work could be adapted to other nuclear waste forms and for longer storage periods.

The tests currently in operation at E-MAD involve isolated, near-surface drywells, above-ground storage casks and a storage simulation test for the measurement of local fuel cladding temperatures. An isolated drywell test has been operating with an electric spent fuel assembly simulator since March, 1978. Its primary objective is to provide temperature measurements from the storage canister outward into the soil for a range of power levels from 1 to 3 kW. The data are used to qualify thermal models and to help demonstrate the decay heat range over which spent fuel could be stored passively without experiencing excessive clad temperatures. Similar test data have been collected from two additional drywells and from an above ground cask containing actual PWR fuel. Those data are also being compared with computer model predictions to develop further confidence in analytical procedures. The storage simulation test is of particular interest since, contrary to the drywell and sealed storage cask tests, measurements of fuel clad temperature throughout the fuel assembly are actually obtained. These data allow the development of correlations between the fuel and canister temperatures which can then be applied to the other fueled tests. Thus, once a canister temperature profile is known, fuel temperature can be inferred.

The E-MAD facility is also equipped with a concrete-lined, air-cooled pit that is used for the short-term storage of canisterized fuel assemblies. Cooling is provided by either forced or natural circulation. The pit, while not intended for long-term storage, could be used to model air-cooled vault operation.

Data from these tests have been analyzed and conclusions are being drawn regarding the thermal performance of spent fuel assemblies in dry storage and also regarding the ability to predict that performance. The results and conclusions from individual tests are reported as tests are completed and examples of issued reports are References 2 through 5. Thus far, however, a single analysis to consolidate results from the individual tests has not been performed. A study of that type is the subject of this report and, specifically, its purposes are:

- To unify the elements of the E-MAD test program and to better understand, as a result, the thermal performance of dry storage systems.
- To assess, in summary form, our ability to thermally analyze near-surface drywells and above-ground storage casks, and
- To identify program needs and requirements which, if satisfied, would significantly improve that ability.

2.0 CONCLUSIONS AND RECOMMENDATIONS

Regarding the near-surface, dry storage of PWR spent fuel assemblies in Nevada Test Site soil, and above-ground storage, the following major conclusions and recommendations can be drawn based upon the thermal analysis and evaluation of experiments performed at the E-MAD facility.

2.1 CONCLUSIONS

- For a decay heat level of 1 kW, the maximum clad temperature for a PWR spent fuel assembly stored in an isolated drywell in Nevada Test Site soil is dependent upon the canister backfill medium as follows:

Helium	-	360°F
Air	-	400°F
Vacuum	-	425°F

- For a 1.0 kW fuel assembly stored in a sealed storage cask of the type currently installed at E-MAD, peak canister and fuel temperatures will be approximately 50°F less than the isolated drywell temperatures.
- With either air or helium backfill, dry PWR fuel assemblies with decay heat levels in excess of 2 kW could be placed in isolated drywells in Nevada Test Site soil without exceeding the current fuel temperature design limit (715°F).
- Using the same limit, fuel assemblies of even higher decay heat levels could be stored in sealed storage casks.
- In Nevada Test Site soil, center to center spacings of 40 feet are sufficient to thermally isolate drywells containing spent fuel with decay heat levels of 2.0 kW or less.
- Peak fuel temperatures depend largely on the soil's thermal conductivity. Therefore, for analysis purposes, the conductivity must be known and its dependency on moisture content must be understood and predictable.
- With accurate soil thermal conductivity input, current thermal models can produce accurate predictions of temperatures outside the canister.

- The sealed storage cask thermal model can produce accurate predictions of canister, liner and concrete temperatures.

- In canisters with a gas backfill, natural circulation currents will redistribute heat, skew the canister heat flux profile towards the top, and affect temperatures near the canister ends.

2.2 RECOMMENDATIONS

- Work should be undertaken to fully analyze E-MAD soil temperature data from the passive heat dissipation tests to better understand moisture effects on soil thermal conductivity and to develop a conductivity model.

- A canister subchannel analysis model to handle internal convection, conduction and radiation should be developed and qualified. The model could then be applied in dry storage design and would be intended for use with various fuel assembly designs.

- The ability of the drywell thermal model to accommodate thermal interaction effects between drywells should be confirmed. This will require experiments with closer drywell spacings and possibly with higher decay heat levels than have been tested previously.

- Experiments should be performed with two BWR spent fuel assemblies encapsulated in a single canister to establish the fuel clad and canister temperature relationship for that situation.

3.0 BACKGROUND

3.1 DRYWELL/SEALED STORAGE CASK DESCRIPTIONS

Two modes for the interim storage of spent PWR/BWR fuel assemblies are being developed and tested at the E-MAD Facility. They involve near-surface drywells (one drywell is depicted in Figure 1) and a Sealed Storage Cask (SSC), shown in Figure 2, for above-ground storage. The drywell design consists of a carbon steel liner grouted into a 26 inch diameter hole drilled to a depth of approximately 23 feet. The liner has a lower section of 18 inch, standard schedule pipe, 17 feet long, while the upper section is 22 inch schedule 60 pipe, 52 inches in length. Shield plug support is provided by the lower liner ledge and the stainless steel canister, which encapsulates the spent fuel, is suspended from the shield plug. The canister/shield plug assembly is installed in the drywell as a unit.

The Sealed Storage Cask, shown in Figure 2, is a reinforced concrete cylindrical structure, 104 inches in diameter and 252 inches high. Embedded in the structure is a carbon steel liner with the same internal configuration as the drywell liner described above and the shield plug/ canister assembly is supported by the liner ledge as in the drywell design. It is noted that the canister design depicted in Figure 2 shows an internal support structure for two BWR fuel assemblies while the drywell canister of Figure 1 is outfitted to accommodate one PWR assembly. Details concerning drywell and SSC features are included in References 5 and 3, respectively.

3.2 DRY STORAGE DESIGN OBJECTIVES

To provide an alternative to the wet storage of spent reactor fuel, the dry-storage concepts described above are being examined. Dry storage periods up to 50 years are contemplated and implementation of the concepts at away-from-reactor and, potentially, at reactor sites is being considered. In addition to the lifetime goal, the dry storage systems must also achieve additional design objectives which are identified below:

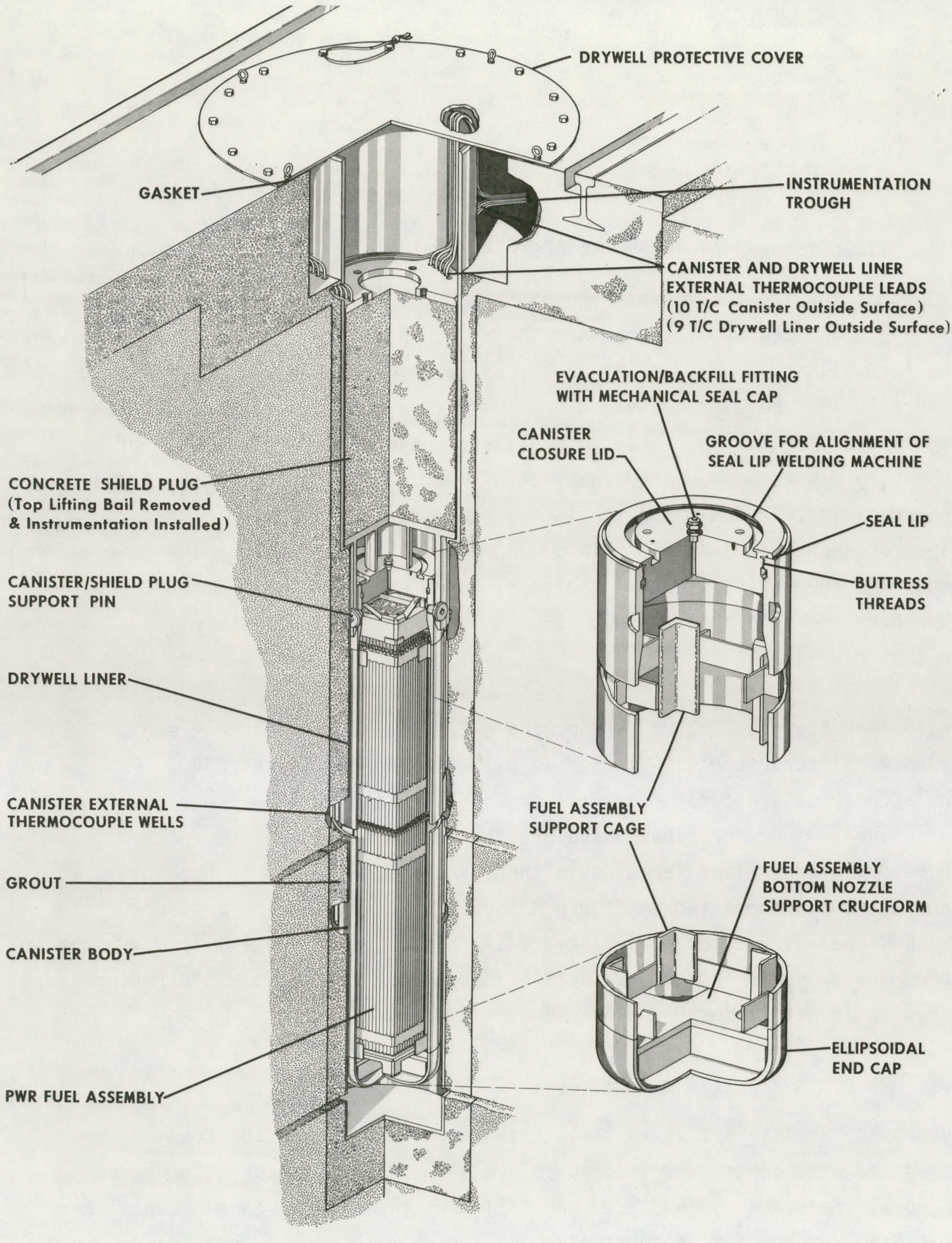


Figure 1. Near-Surface Drywell Configuration

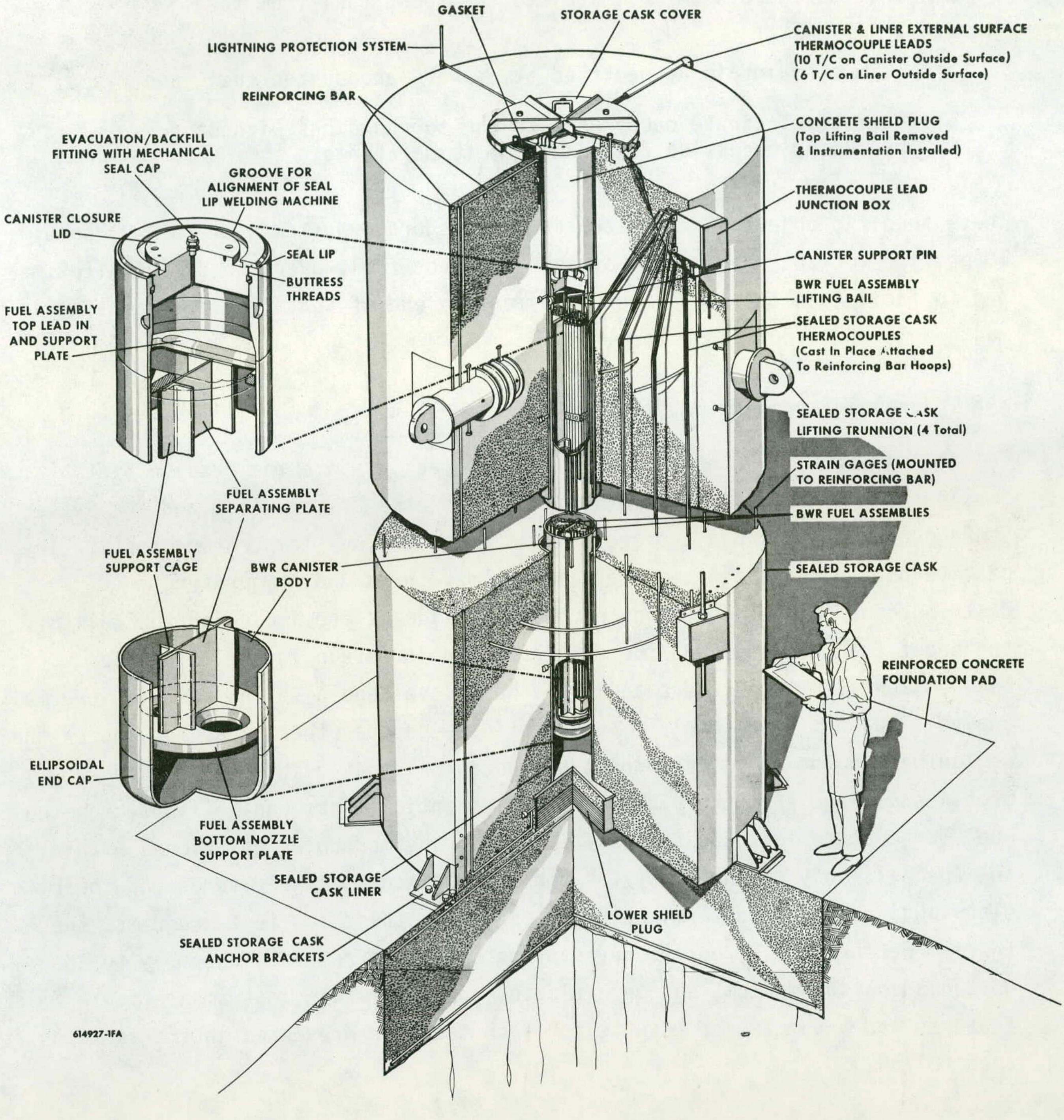


Figure 2. Sealed Storage Cask Configuration

- The storage system must isolate the spent fuel from the environment,
- It must maintain a specified atmosphere around the fuel, and
- It must dissipate decay heat to the surroundings without producing excessive fuel and clad temperatures.

These specific objectives all stem from the storage system's overall purpose: To provide for the dry storage of spent reactor fuel, over the design lifetime, and to facilitate the fuel's retrieval at the end of that period in a safe, manageable and predictable form.

3.3 E-MAD TEST PROGRAM REVIEW

The thermal tests in operation at the E-MAD facility are the passive heat dissipation tests (Soil Temperature Test, Isolated Drywell Test and the Sealed Storage Cask Test) and a storage simulation test (Fuel Temperature Test). The passive heat dissipation tests provide temperatures and temperature distributions in the heat transfer media outside of and including the wall of the spent fuel canister and the data are used in developing relationships between canister temperature and decay heat level and also in verifying thermal analysis methods. The Fuel Temperature Test, on the other hand, focuses on the region within the canister. The test concept is that axial temperature profiles derived from the passive heat dissipation tests can be imposed on the Fuel Temperature Test canister. Then, using thermocouples positioned within the fuel assembly contained by the canister, cladding temperatures and their distributions can be determined. Thus, between these two test programs, the thermal performance of entire dry storage systems, from fuel assembly to the heat dissipating medium, can be evaluated and analyzed. Instrumentation features and a summary of results for each test are presented in the sections that follow.

3.3.1 SOIL TEMPERATURE TEST

This test was placed in operation in March, 1978 and has been operated continuously since then at simulated decay heat levels of 1, 2 and 3 kW. The test arrangement (shown in Figure 3) consists of a carbon steel drywell liner,

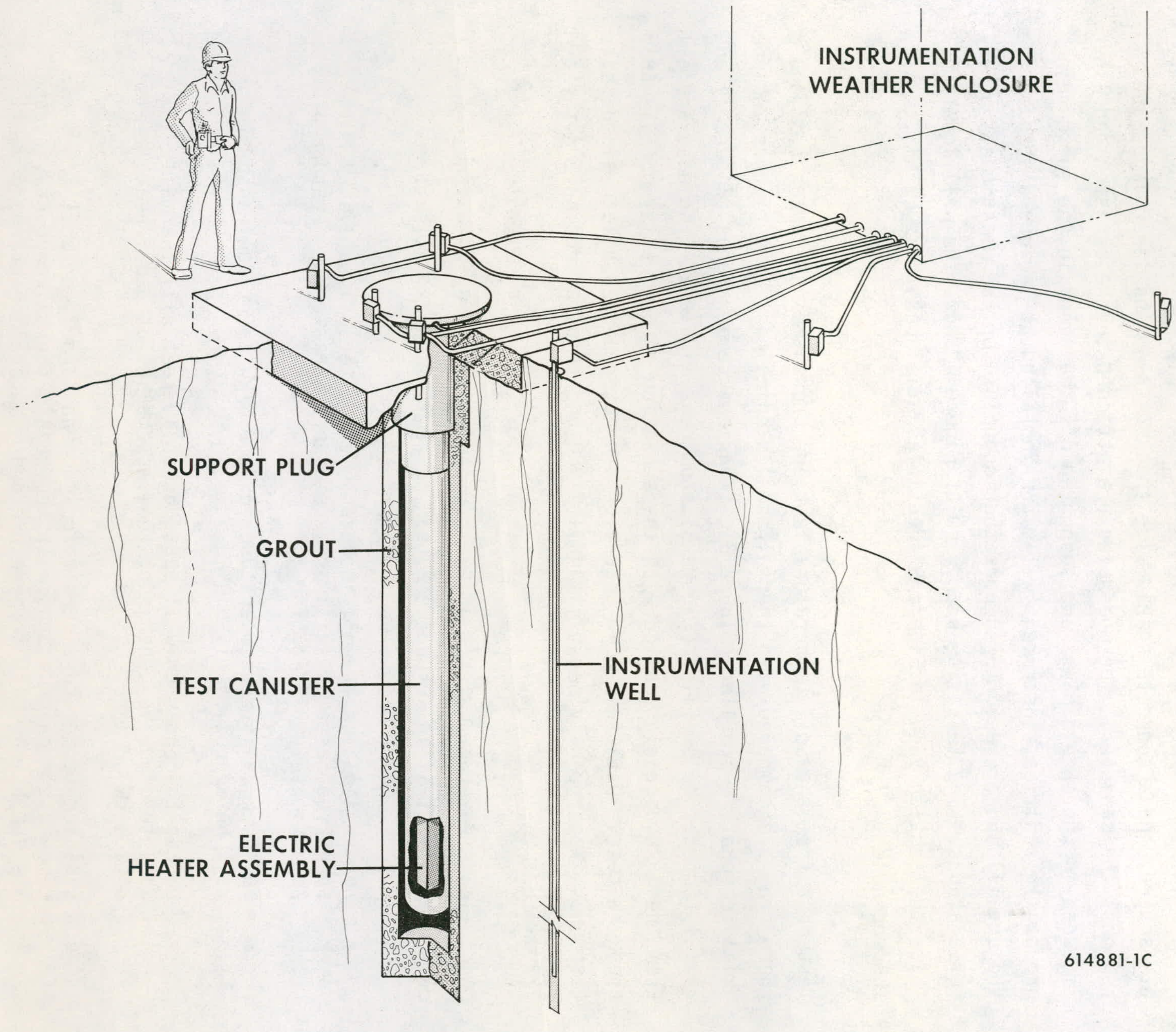


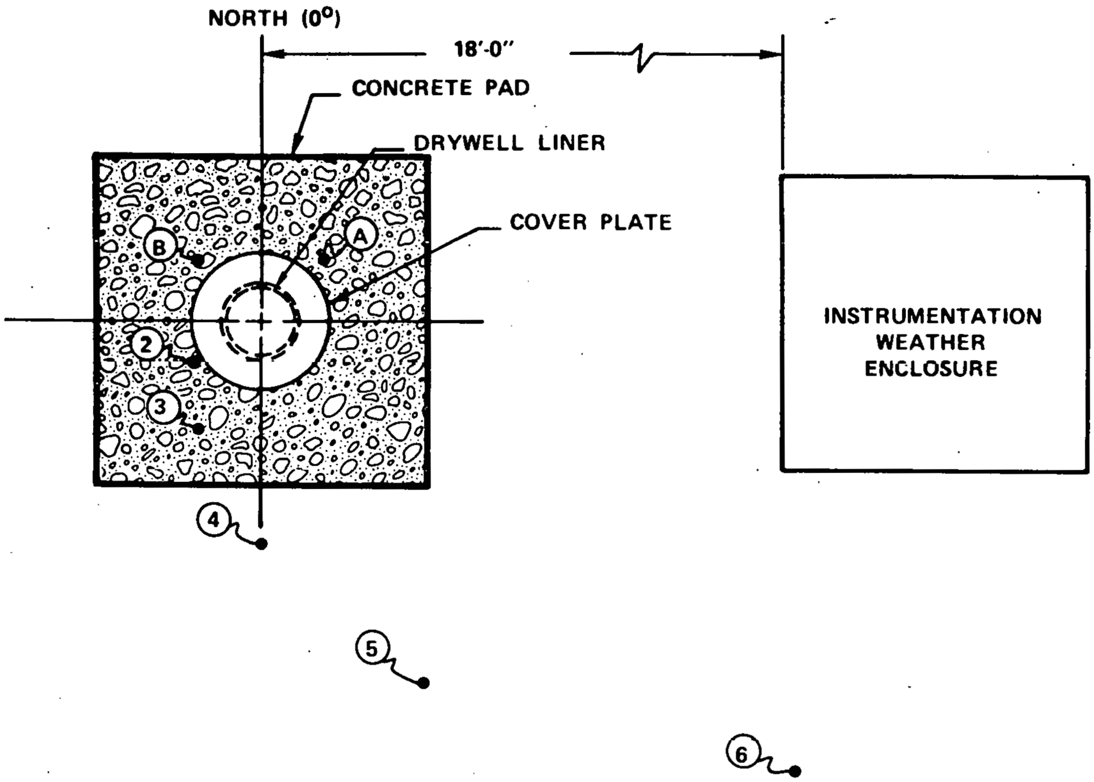
Figure 3. Soil Temperature Test Arrangement

a stainless steel canister containing an assembly of electric heaters in an air atmosphere, and a concrete shield plug that rests on the liner ledge and supports the canister. Thermocouples are attached to the canister and liner, imbedded in the shield plug, and supported off the liner in the surrounding grout. In addition, instrument wells are installed at various distances from the drywell and are used to support thermocouples for the measurement of soil temperatures. The test site plan view of Figure 4 shows the well locations while the section view in Figure 5 identifies axial positions of all test thermocouples.

Test data from the Soil Temperature Test are presented in Figures 6, 7 and 8 where they are compared with thermal model predictions. The figures include axial temperature profiles (Figure 6), transient temperatures (Figure 7) and radial temperature profiles (Figure 8) from near midplane. The data are all from the 1 kW operating period with the exception of one radial profile from the 2 kW test. Data from 3 kW operation are not reported herein since that test phase was recently begun in April, 1980 and temperatures have not yet stabilized.

Conclusions from the analysis of Soil Temperature Test data, which are developed in detail in Reference 2, can be summarized as follows:

- For an isolated drywell in Nevada Test Site soil, a 1.0 kW PWR spent fuel assembly will produce a peak canister temperature of approximately 275°F.
- The peak canister temperature for a 2.0 kW spent fuel assembly will be approximately 510°F.
- Center-to-center drywell spacings of 40 feet will thermally isolate drywells containing fuel assemblies at decay heat levels of 2.0 kW or less.
- Canister temperature predictions depend largely on soil temperature calculations. If the soil's thermal conductivity and its variations with temperature and moisture are known, drywell analysis procedures exist which can accurately predict the peak canister temperature and temperature distributions throughout the storage system.



INSTR. WELL	RADIUS	THERMOCOUPLE ORIENTATION	WELL DEPTH	NO. OF THERMOCOUPLES
A	9"	0°**	(ON LINER)	16
B	10.8"	315°	(SUPPORTED OFF LINER)	10
2	21.0"	240°	303"	13
3	33.0"	210°	220"	10
4	60.0"	180°	303"	11
5	108.0"	155°	201"	8
6	189.0"	130°	153"	7
*REF.	60.0'	30°	314"	9

–ADDITIONAL THERMOCOUPLES: 11 ON SHIELD PLUG & 13 ON CANISTER
–ALL INSTRUMENTATION WELLS ARE 1" IN DIAMETER
–A & B ARE STAND PIPES FOR THERMOCOUPLES SUPPORTED BY THE LINER

*REFERENCE WELL NOT SHOWN
**THERMOCOUPLE LOCATED AT 0°, STAND PIPE LOCATED AT 45°

615261-8AA

Figure 4. Plan View of Thermocouple Locations - Soil Temperature Test

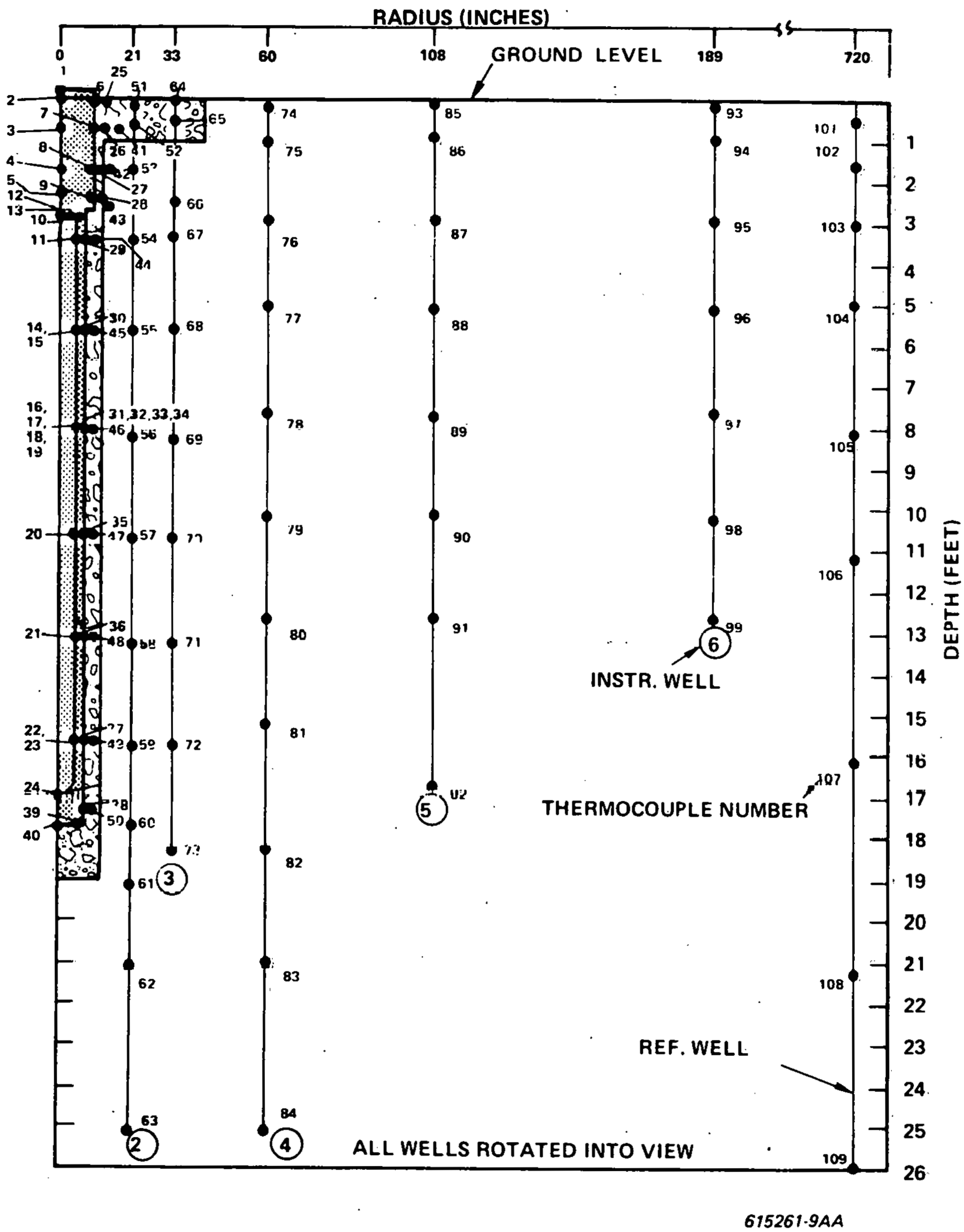


Figure 5. Section View of Thermocouple Locations - Soil Temperature Test

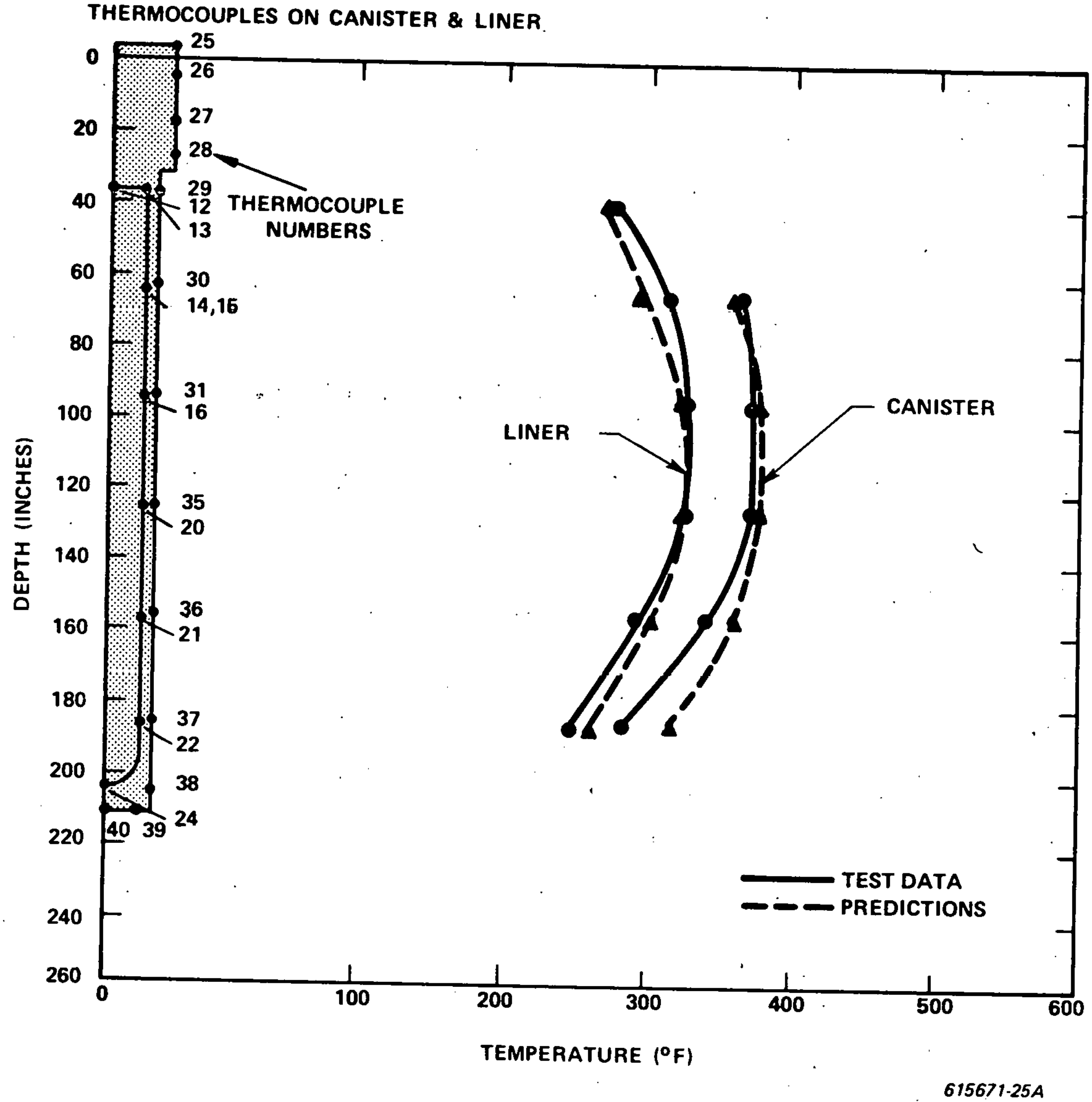


Figure 6. Axial Temperature Data and Predictions for 1 kW Operation, August, 1978 - Soil Temperature Test

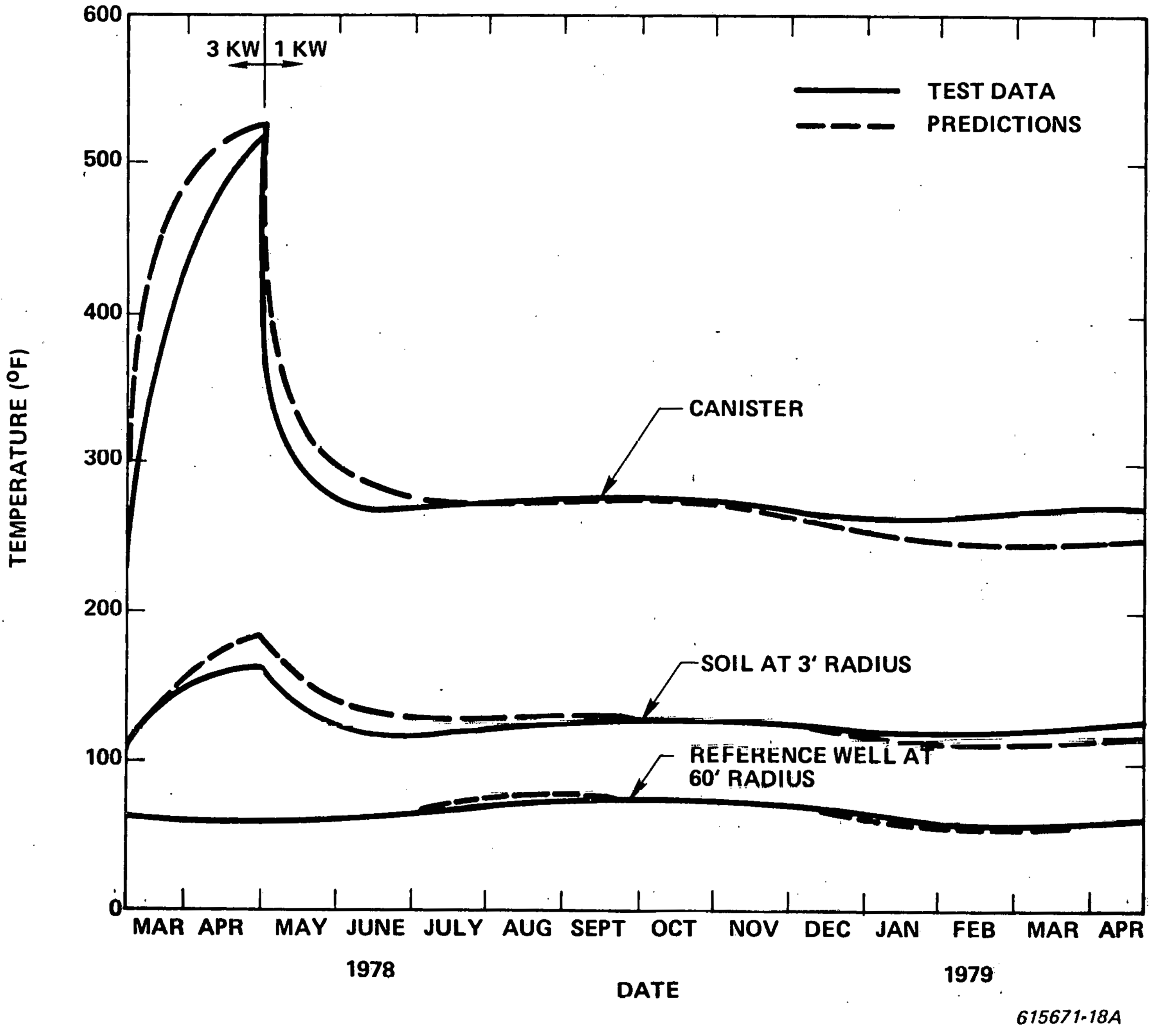


Figure 7. Transient Temperature Data and Predictions for the 11 Foot Depth During 1 kW Operation - Soil Temperature Test

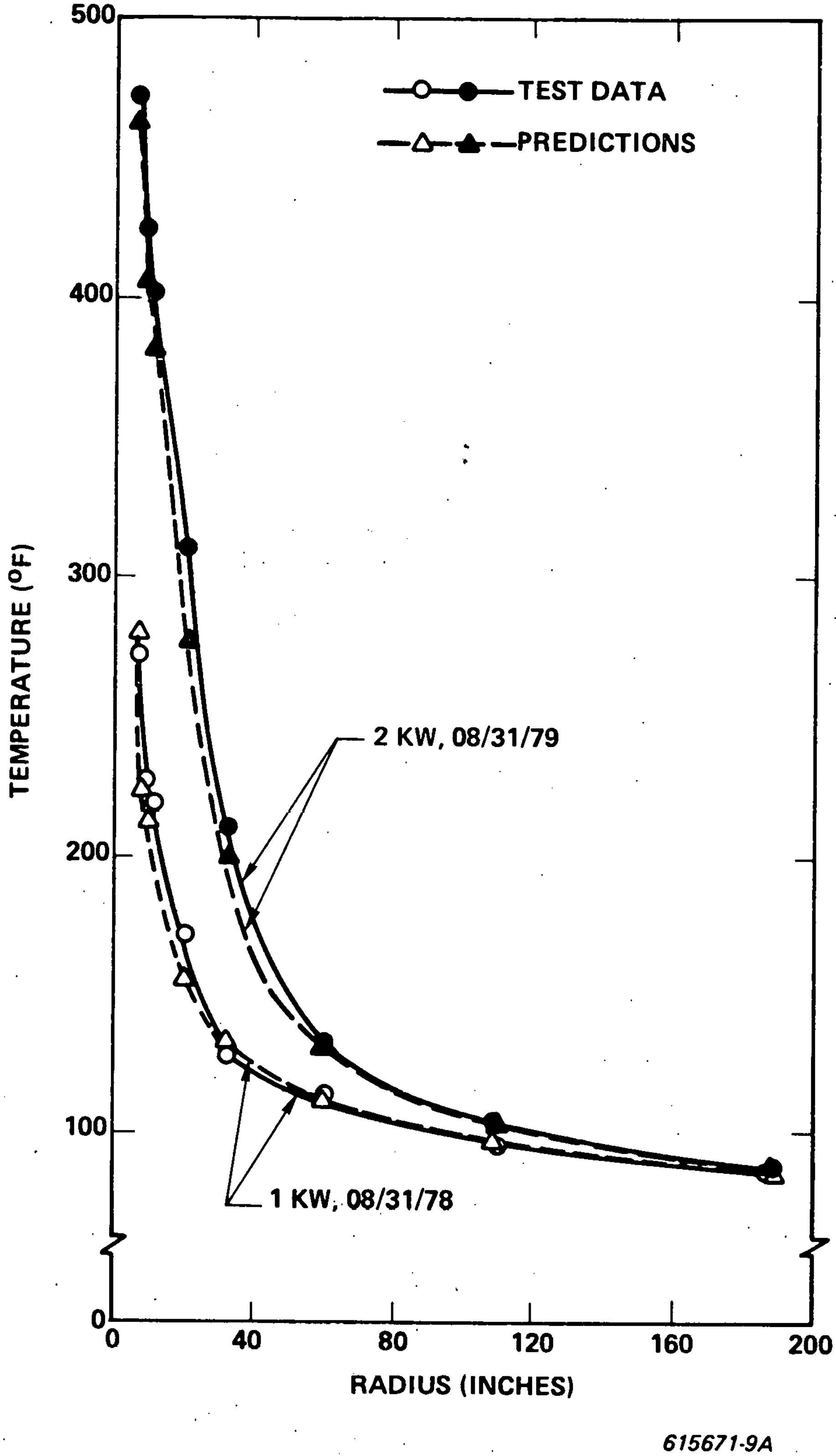


Figure 8. Radial Temperature Profile Comparison for the 8 Foot Depth During 1 kW and 2 kW Operation - Soil Temperature Test

- In an air-filled canister, natural circulation currents will skew the canister heat flux distribution towards the top and affect temperatures particularly at elevations near the canister ends.

3.3.2 ISOLATED DRYWELL TESTS

Four drywells of the type depicted in Figure 1 are installed at E-MAD and are arranged as shown in Figure 9. As indicated in Figure 9, space is allocated for a fifth drywell (Drywell No. 4) and may be used at some future time. In January, 1979, two encapsulated PWR spent fuel assemblies (helium backfill) were placed in storage in Drywells 3 and 5. At the time of emplacement, they had been out-of-reactor approximately 3 years and their decay heat levels were estimated at 1.0 to 1.1 kW. The canister and liner of each drywell were equipped with thermocouples at elevations identified in Figure 10 and additional thermocouples were placed in the soil near each drywell using instrumentation wells. The elevations of the soil thermocouples are also identified in Figure 10 and the distances of each instrumentation well from the drywell centerline are shown in Figure 9.

Drywell temperatures were recorded daily starting with canister emplacement and continuing to August, 1980 when the canister/drywell arrangement was altered. Drywell 5 temperatures recorded during that period are displayed in Figures 11 and 12 and compared with predictions. Data from all Drywell 5 and Drywell 3 thermocouples are presented in Reference 5 and discussed in detail.

Conclusions from the analysis of data from the Isolated Drywell Tests include the following:

- The peak canister temperature recorded during drywell operation was 254°F and occurred approximately 7 months after canister emplacement.
- Due to seasonal soil temperature variations, the peak canister temperature and its time of occurrence are dependent upon the emplacement time.
- Canister temperatures depend upon seasonal air temperature variations but not on diurnal variations.

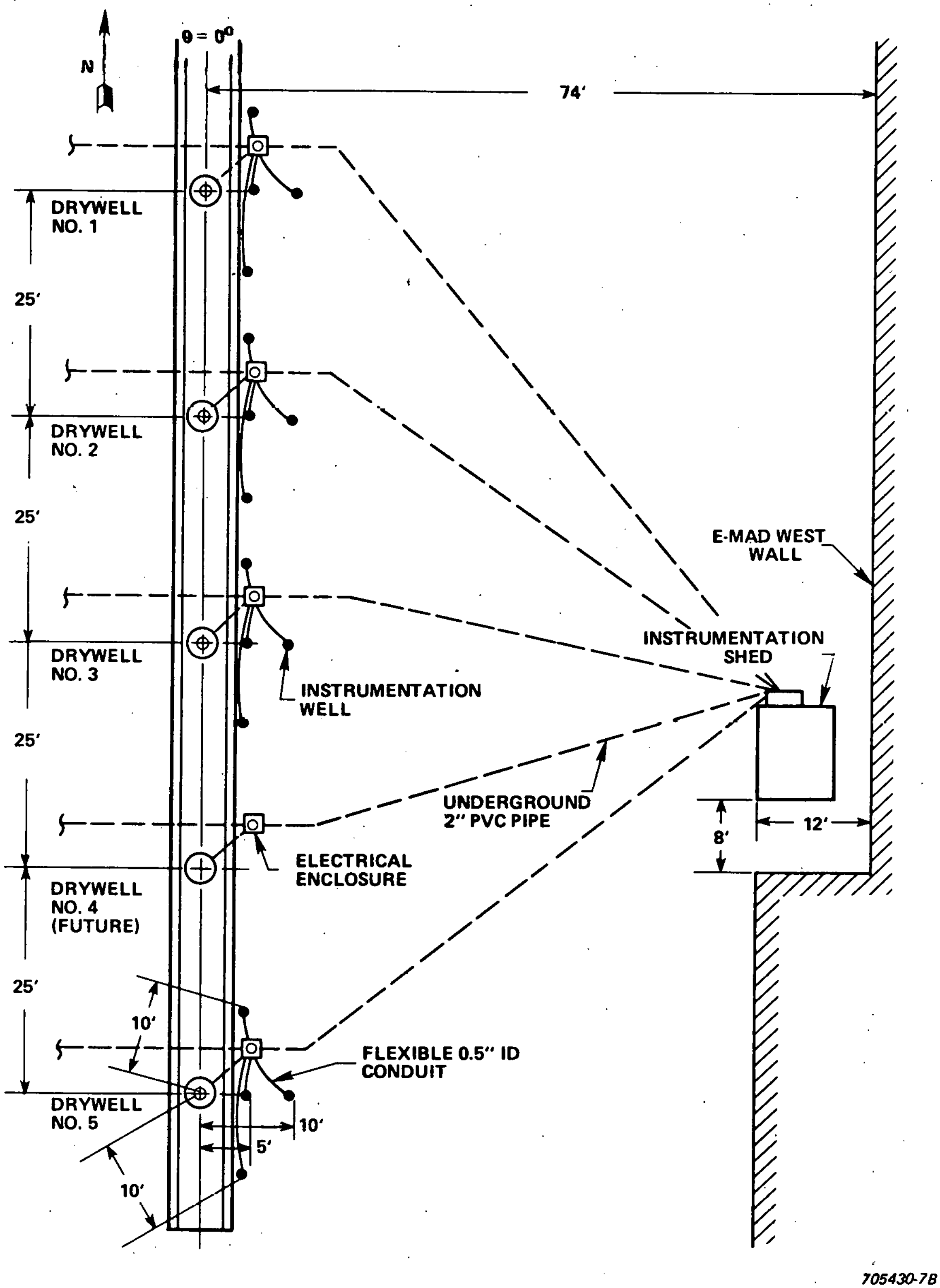


Figure 9. Plan View of Drywell Storage Area

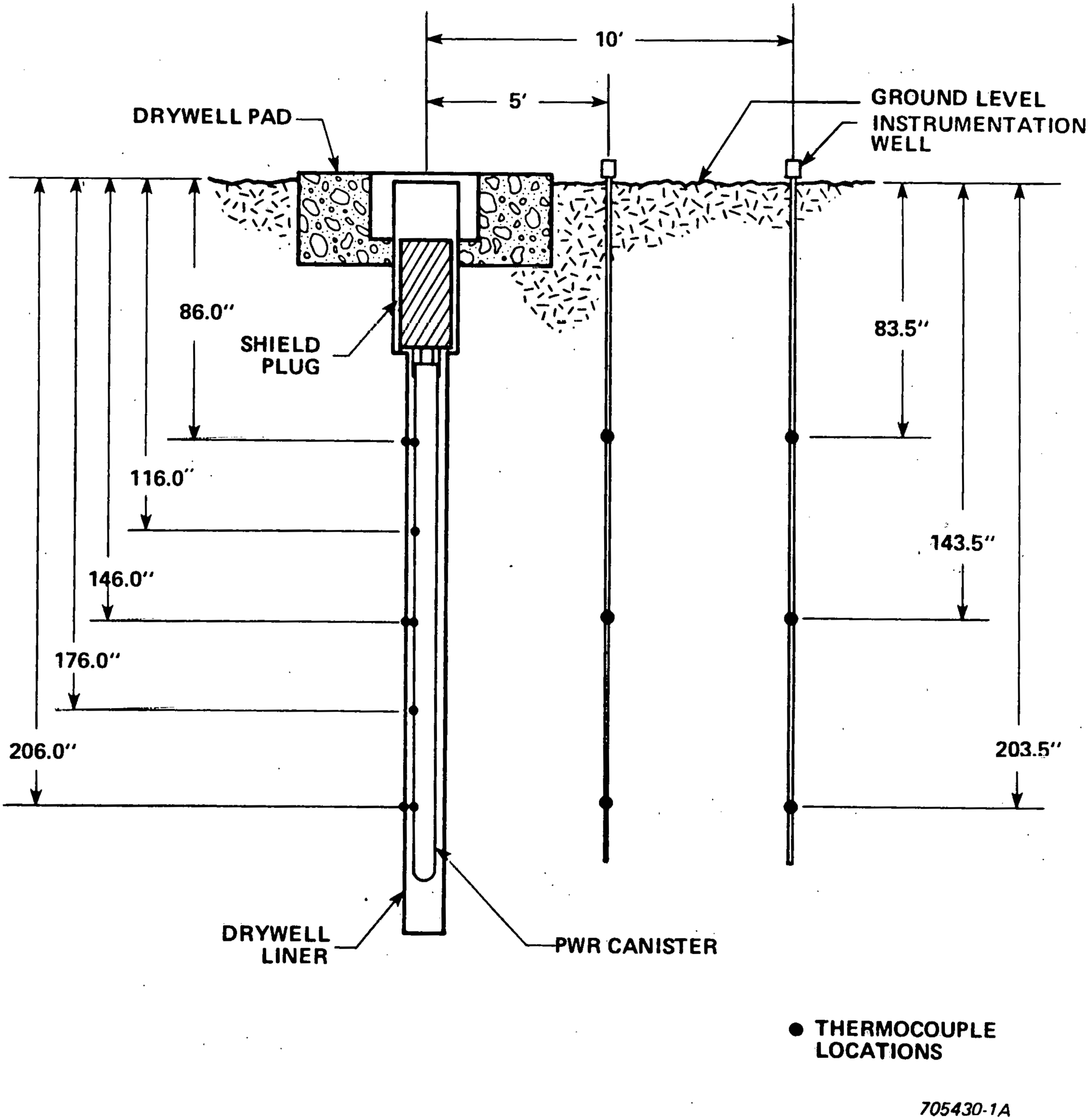


Figure 10. Typical Drywell Thermocouple Elevations

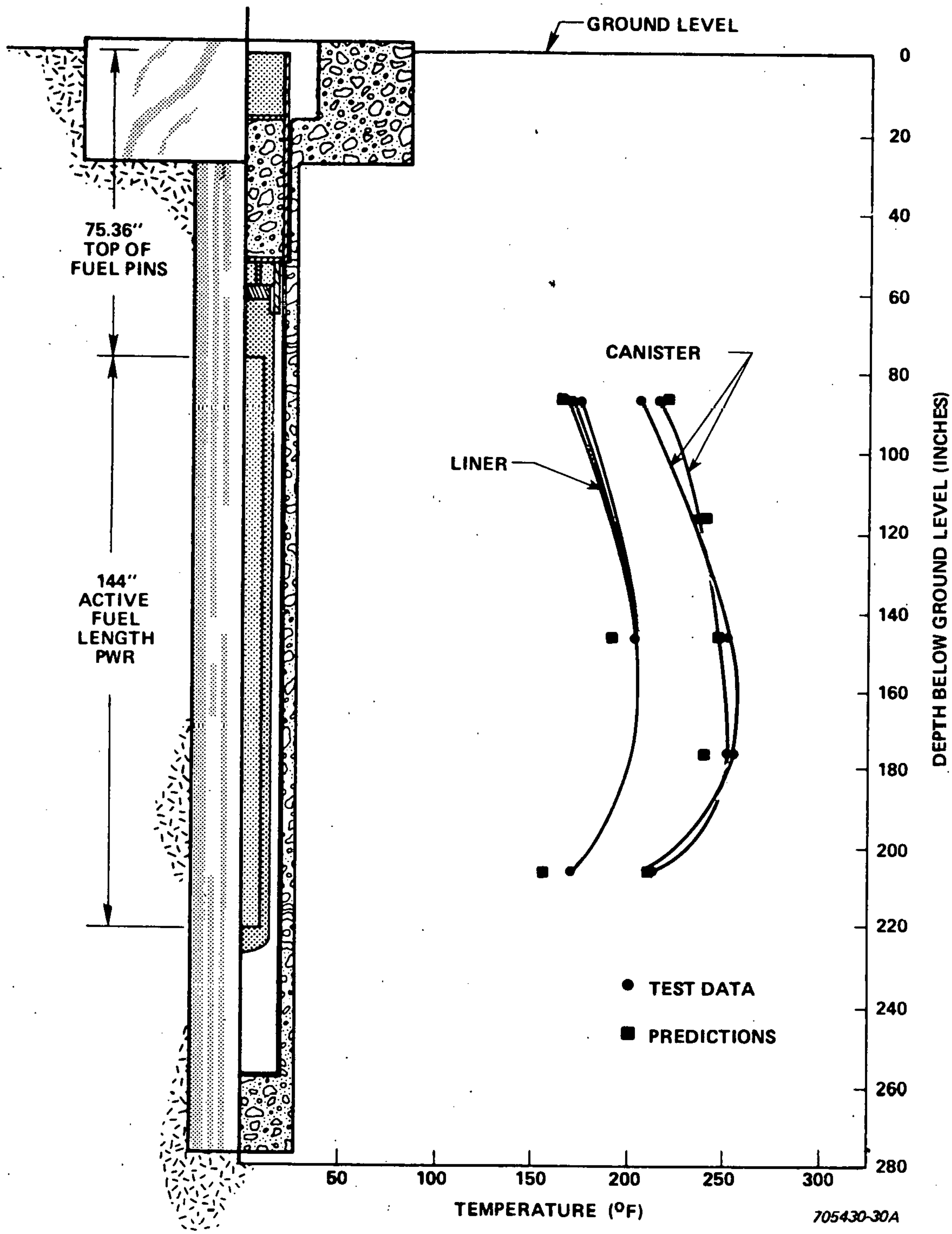
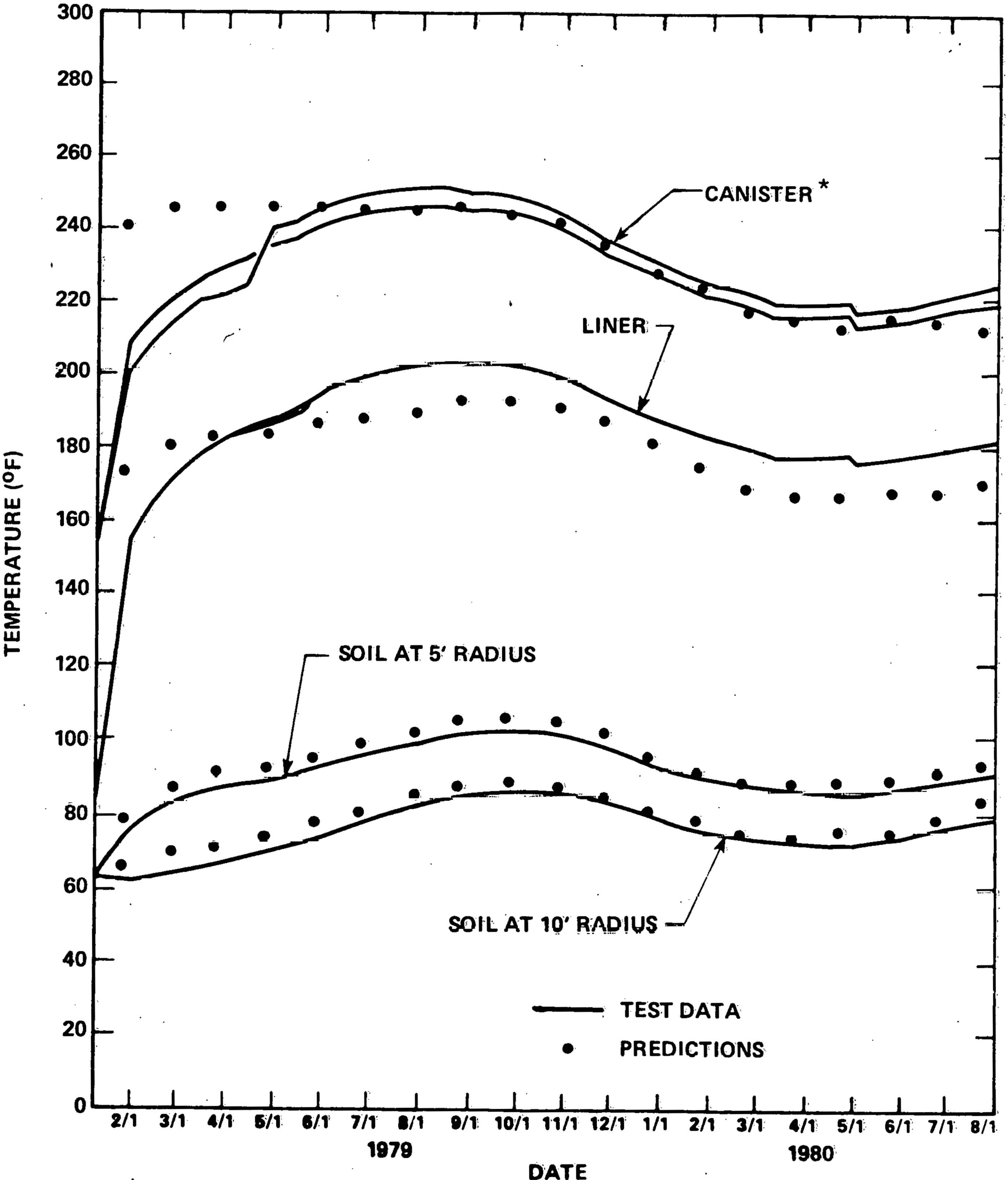


Figure 11. Test Data and Predictions for Drywell 5, August, 1979, Decay Heat Level ≈0.9 kW - Isolated Drywell Test



*Two Azimuthal Thermocouple Locations

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Figure 12. Transient Temperature Data and Predictions at Midplane for Drywell 5 - Isolated Drywell Test

- Canister, liner and soil temperatures were accurately predicted. As in the Soil Temperature Test, the quality of the predictions depends largely upon the soil thermal conductivity input.

It is noted that the Soil Temperature Test and tests with Drywells 3 and 5 all pertain to isolated drywell operation. However, qualified analysis procedures must also be available for use when there is appreciable thermal interaction between adjacent drywells. Therefore, experiments should be conducted in which decay heat levels and drywell spacings are sufficient to produce that interaction and the resulting test data will then be used to confirm the ability of the current thermal model to predict it.

3.3.3 SEALED STORAGE CASK TEST

Two sealed storage casks are installed at the E-MAD site and testing was begun in December, 1978 when a canister containing a PWR fuel assembly (1.1 kW) was installed in one SSC. The cask assembly (canister, liner and concrete) was instrumented with thermocouples and data collection has continued from canister emplacement to the present. A study of all data collected was recently completed, Reference 3, and it produced the following conclusions regarding SSC operation and analysis:

- The peak SSC canister temperature was 201°F and occurred approximately 7 months after canister emplacement.
- Plots of canister temperature vs. time roughly parallel the seasonal air temperature variations.
- Diurnal air temperature variations do not affect temperatures inside the outer 15 inches of concrete.
- The thermal model produced accurate predictions of transient temperatures and temperature distributions.
- In an SSC, the thermal resistance between canister and ambient air depends more heavily on the canister/ liner component and to a lesser extent upon the resistance of the heat-dissipating medium (concrete).

A sampling of SSC test data is compared with thermal model predictions in Figure 13, 14 and 15. Transient temperatures and axial and radial profiles are included.

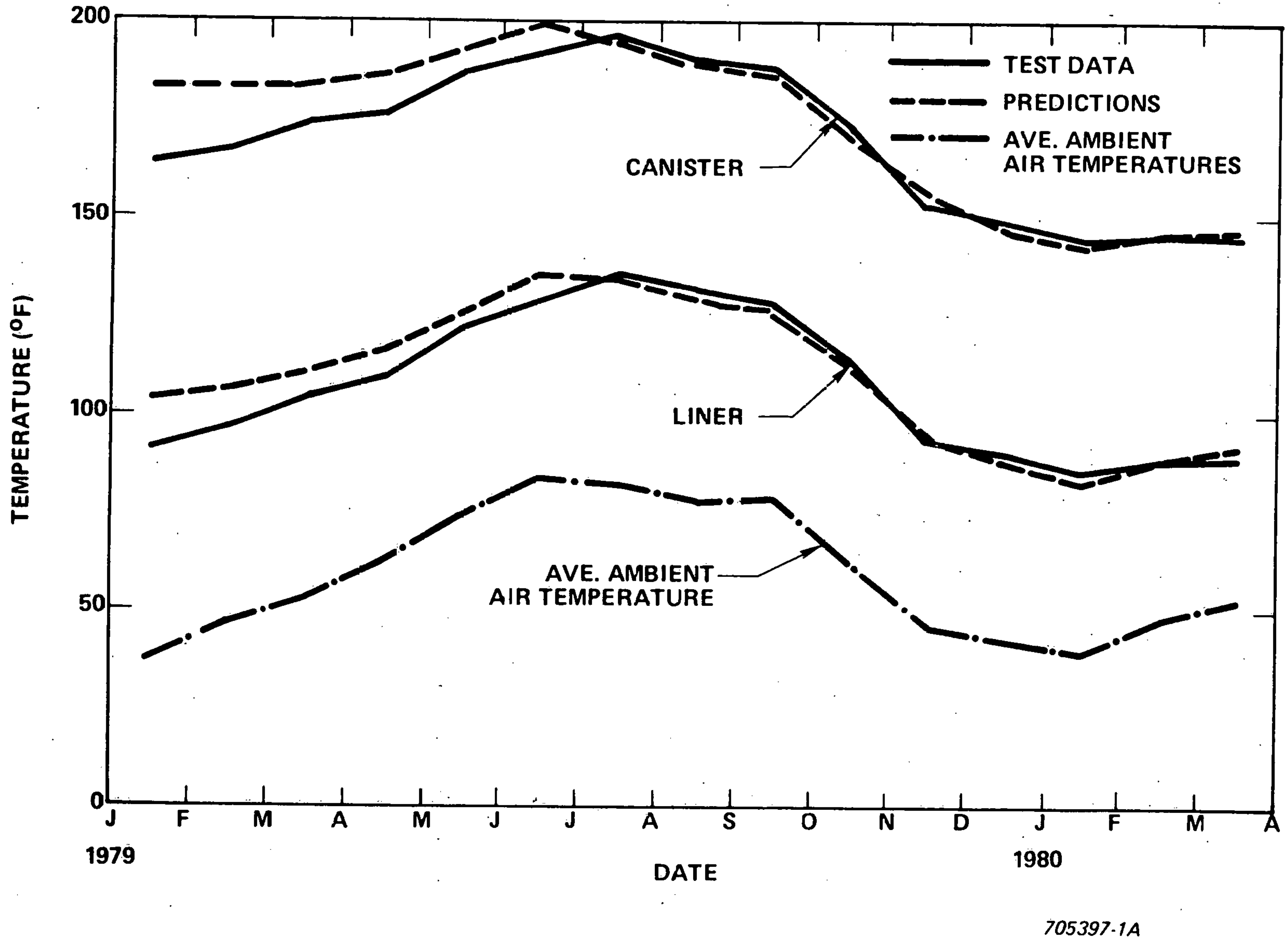


Figure 13. Transient Test Data and Predictions at Midplane - Sealed Storage Cask Test

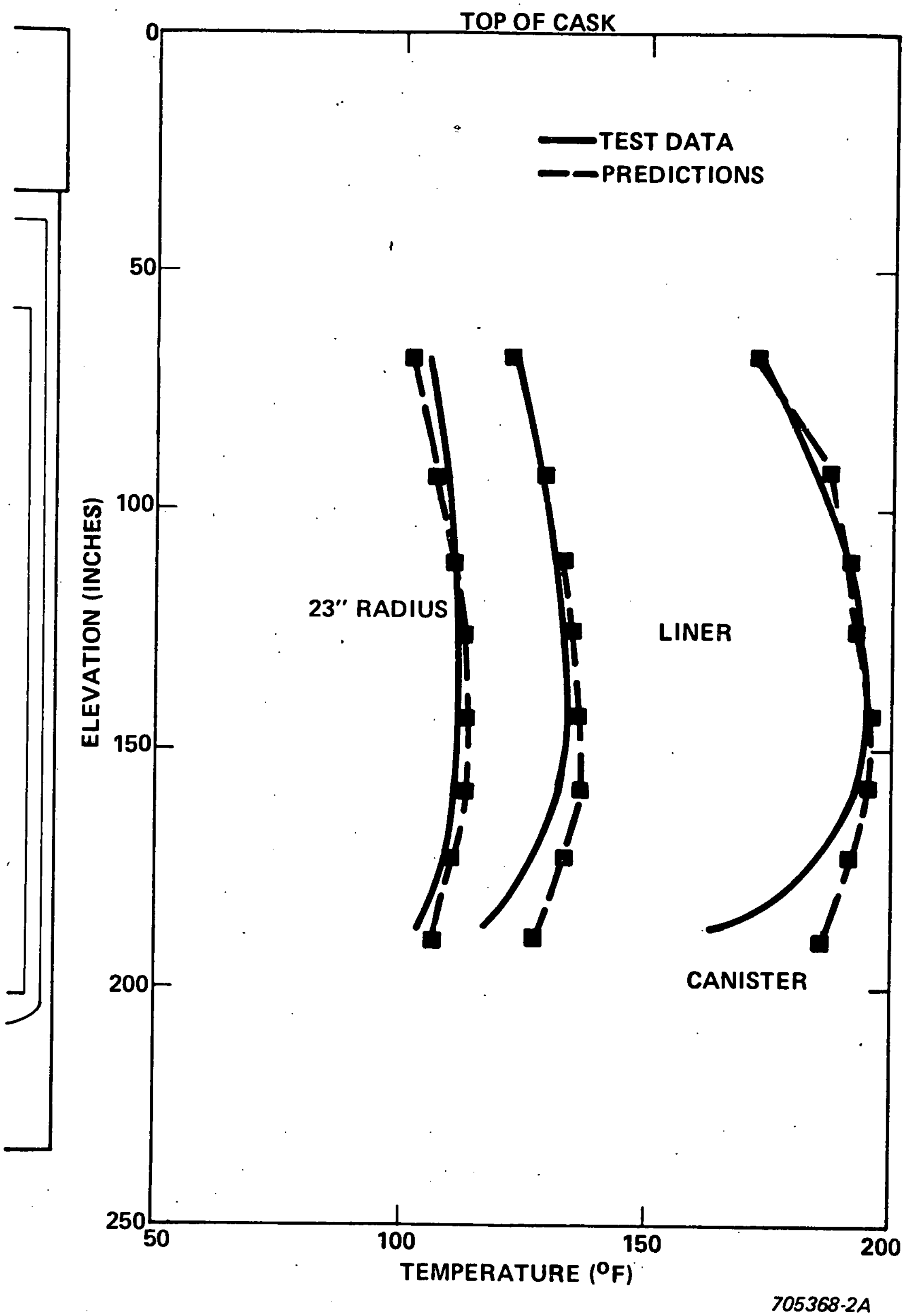


Figure 14. Axial Temperature Data and Predictions, July, 1979, Decay Heat Level ≈0.9 kW - Sealed Storage Cask Test

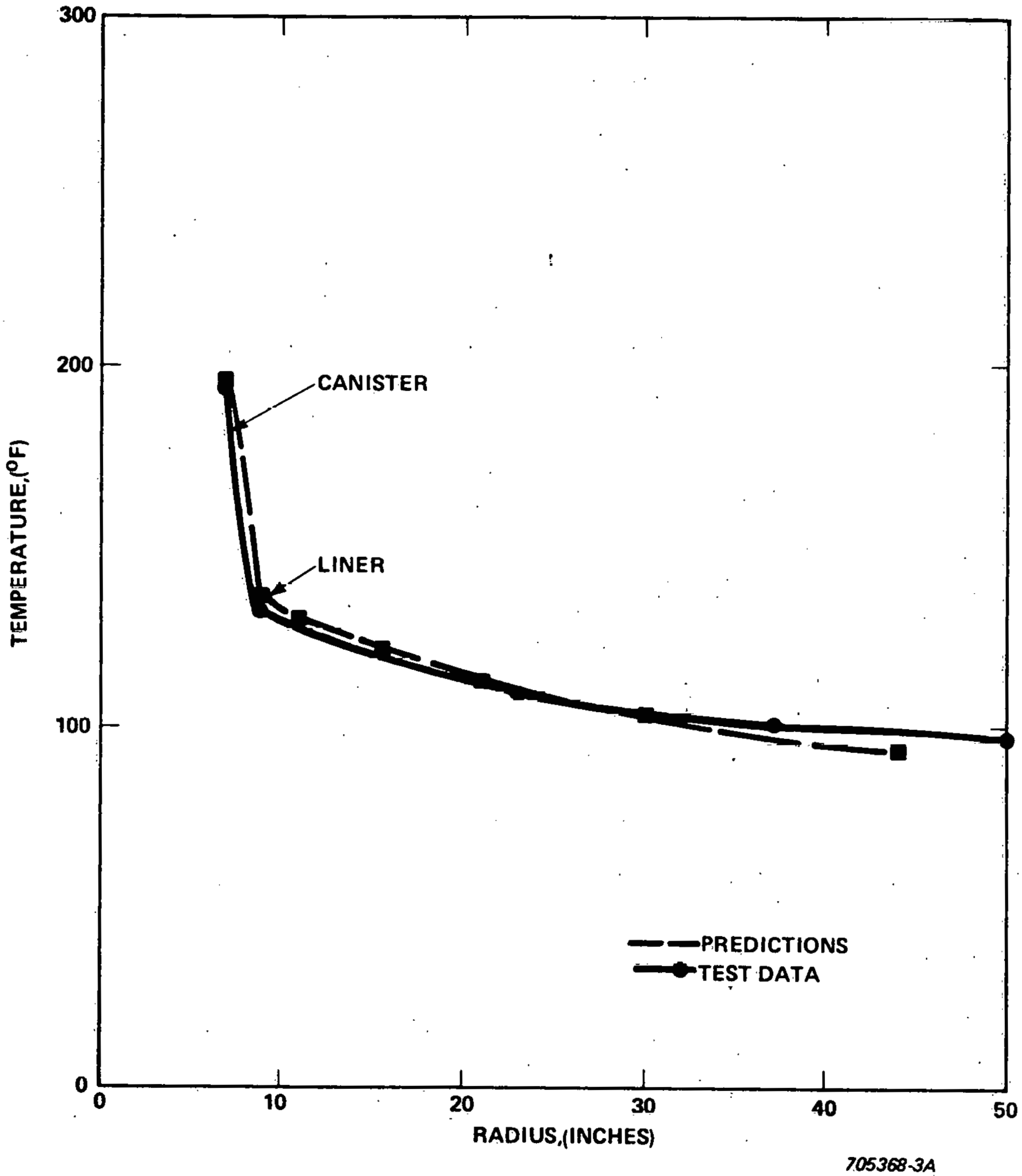


Figure 15. Radial Temperature Data and Predictions, July, 1979, Decay Heat Level ≈0.9 kW - Sealed Storage Cask Test

3.3.4 FUEL TEMPERATURE TEST

Because the canisters in the storage cells were designed with no internal instrumentation to measure fuel temperature (to avoid instrument penetrations in canisters outside the E-MAD facility), the Fuel Temperature Test (FTT) was developed. The FTT apparatus, shown in Figure 16, consists of a drywell liner supported in a test stand inside the E-MAD West Process Cell. Inside of the liner is a canister containing a single PWR spent fuel assembly. The canister is fitted with a bolted closure lid from which 15 thermowells are suspended. The wells fit inside the fuel assembly guide thimbles and contain thermocouples at seven axial elevations for the measurement of fuel temperatures. The closure lid also contains a fitting to which an evacuation and backfill system can be attached. Therefore, the FTT system can be operated and data collected with the canister evacuated or backfilled with various gaseous media. Electrical band heaters are positioned around the liner and these are used to produce a desired axial temperature profile on the FTT canister. Therefore, canister temperature profiles from the passive heat dissipation tests described above can be imposed on the canister and the corresponding fuel temperatures determined.

A variety of tests has been completed using the FTT system and results are analyzed and reported in Reference 4. The work has produced the following data and conclusions which are significant in the continuing effort to evaluate and compare the various dry storage modes and canister backfill media.

- For an encapsulated 1.0 kW PWR spent fuel assembly placed in dry storage at the Nevada Test Site, the peak fuel cladding temperature varies as follows with the storage mode/backfill combination:

Isolated drywell/Air	400°F
Isolated drywell/Helium	360°F
SSC/Helium	320°F

- Peak fuel cladding temperatures measured for a uniform axial canister temperature of 500°F (maximum temperature tested) were about 550°F for a helium backfill and 575°F for an air backfill.

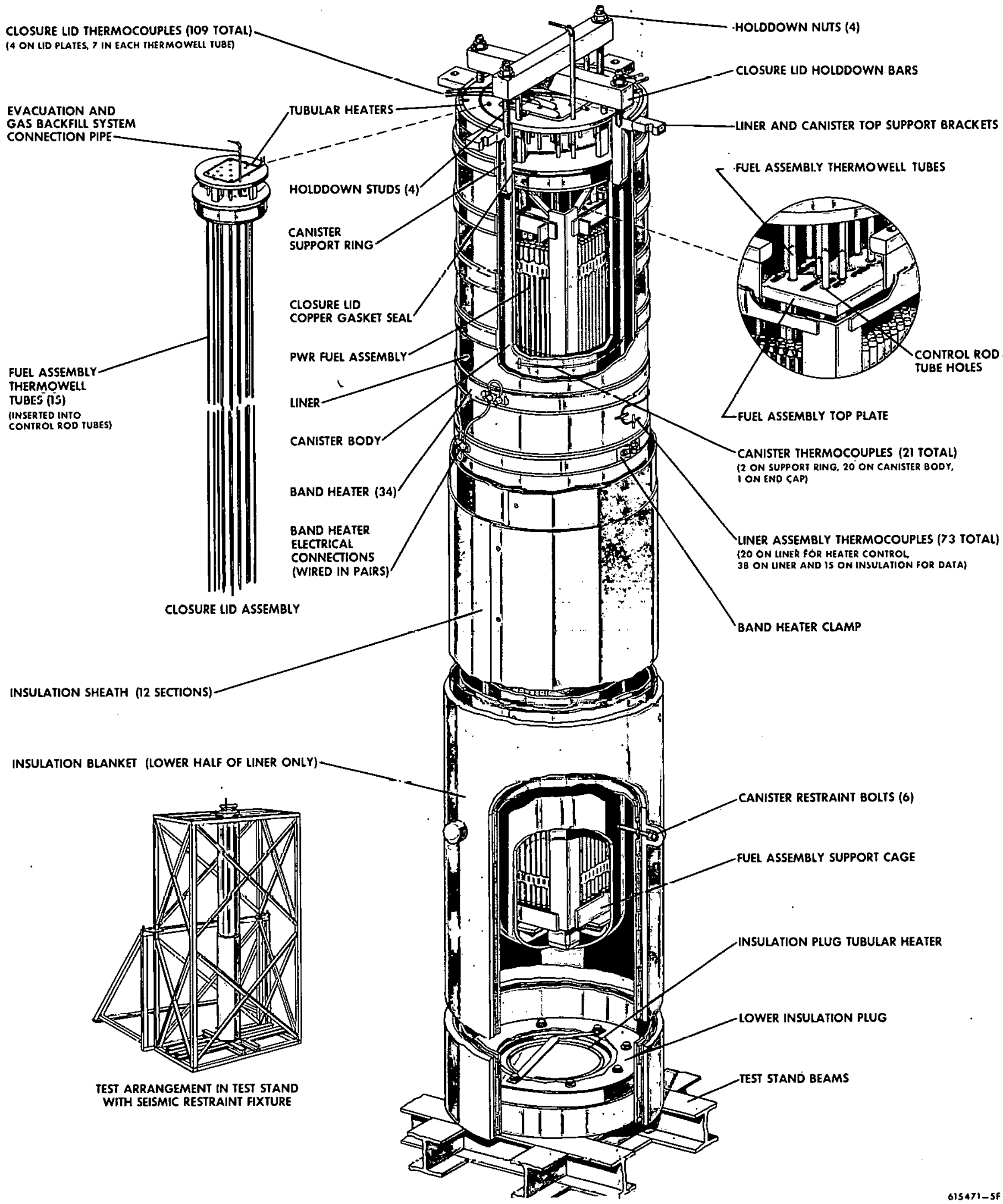


Figure 16. Fuel Temperature Test Arrangement

FTT data are graphed in Figure 17 where they are combined with calculations and canister temperature data to project maximum dry storage decay heat levels. The canister temperature curve in Figure 17 should not depend significantly upon the backfill medium and it is developed from a combination of Isolated Drywell and Soil Temperature Test data. However, as indicated by the FTT data points, the peak fuel temperature does depend upon the backfill. In Figure 17, the maximum fuel temperature curve, applying to a theoretical vacuum, has been drawn based upon FTT data at 0.9 kW and the analysis method described in Reference 6. The intersection of this curve with the current clad temperature design limit (Reference 7) defines the maximum decay heat level which could be accommodated by an isolated, near-surface drywell. It is apparent, therefore, that with either air or helium, dry PWR fuel assemblies with decay heat levels in excess of 2 kW could also be placed in drywell storage in Nevada Test Site soil without exceeding the design limit. Using the same limit, a spent fuel assembly with an even higher decay heat level could be stored in the SSC configuration.

Additional test data from the FTT are provided in Figures 18 and 19. The canister temperature profiles in Figure 18 are based on data from the Soil Temperature Test. They were imposed on the FTT canister and the resulting peak fuel temperature profiles for the canister evacuated and for an air backfill are shown. Similar test data are presented in Figure 19 for Drywell No. 5. Peak fuel temperature profiles are shown for a helium backfill as well as for the air and vacuum cases.

It is noted that all FTT work to date pertains to PWR spent fuel and consideration should be given to the need for similar experimentation with BWR fuel. Of particular importance will be the fuel clad and canister temperature relationship and the extent of circumferential temperature variations caused by the side-by-side encapsulation of two BWR spent fuel assemblies in a single canister.

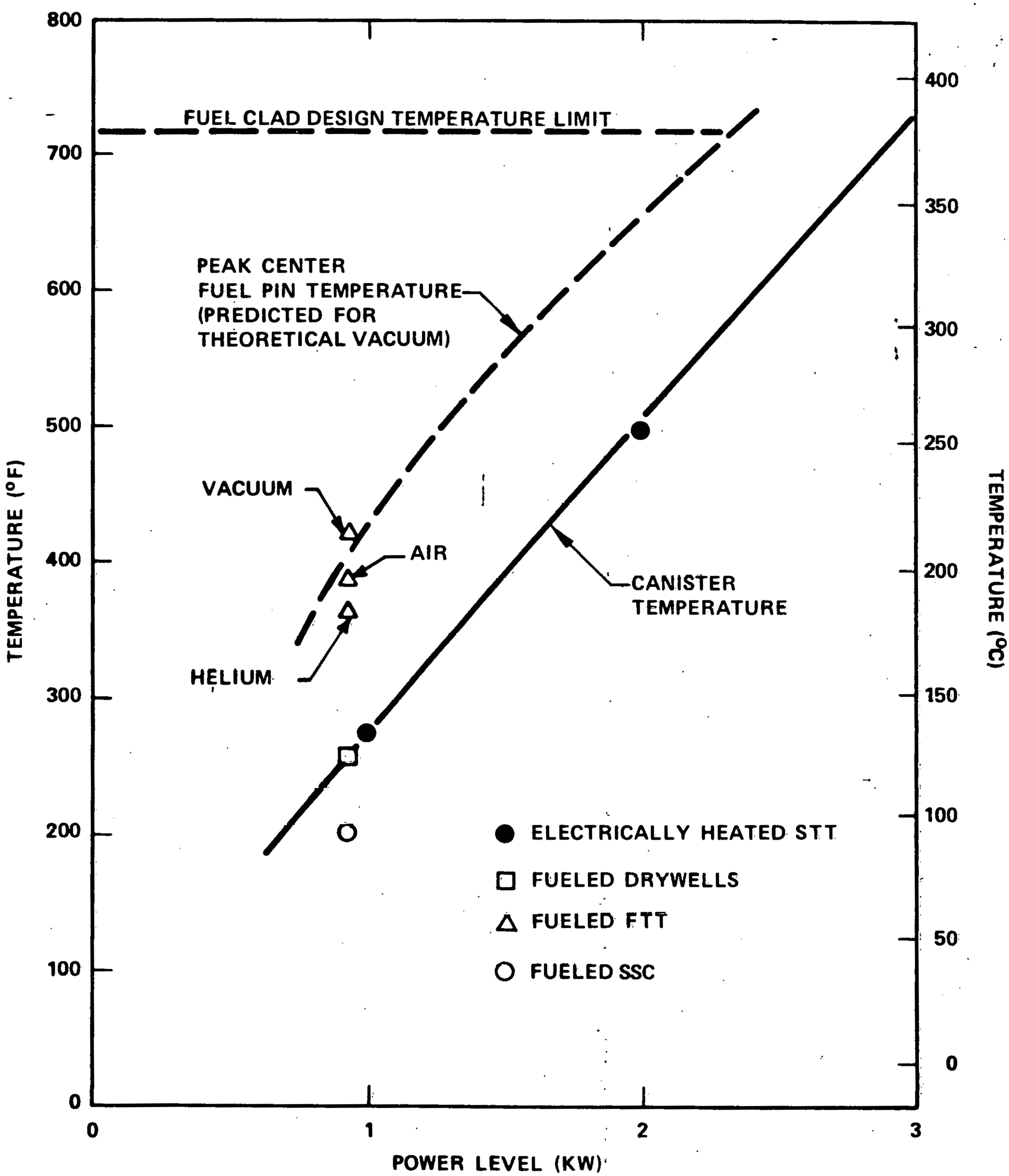


Figure 17. Summary of Fuel and Canister Temperature Data

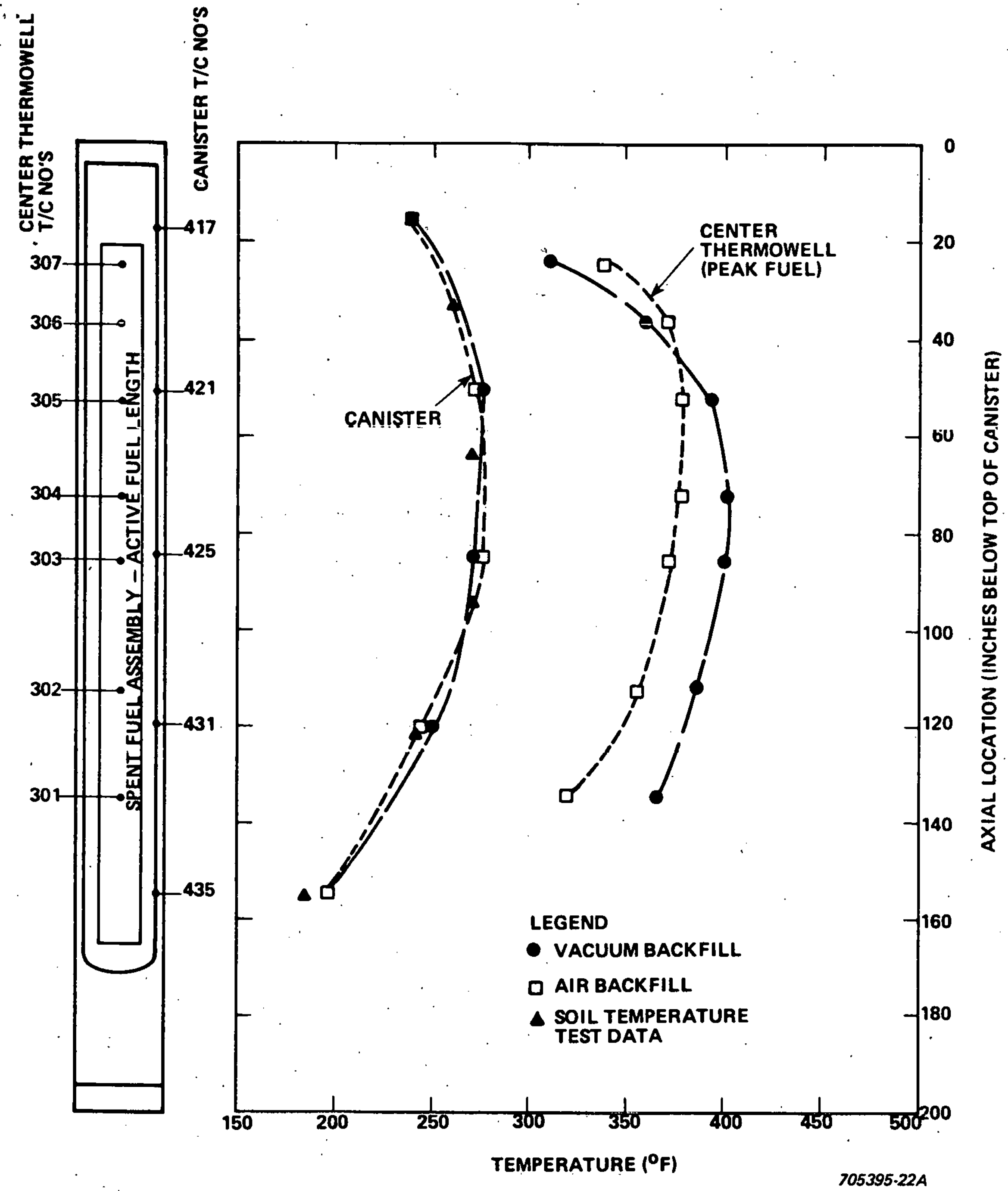


Figure 18. Fuel Temperature Test Profiles for Soil Temperature Test Canister Profile

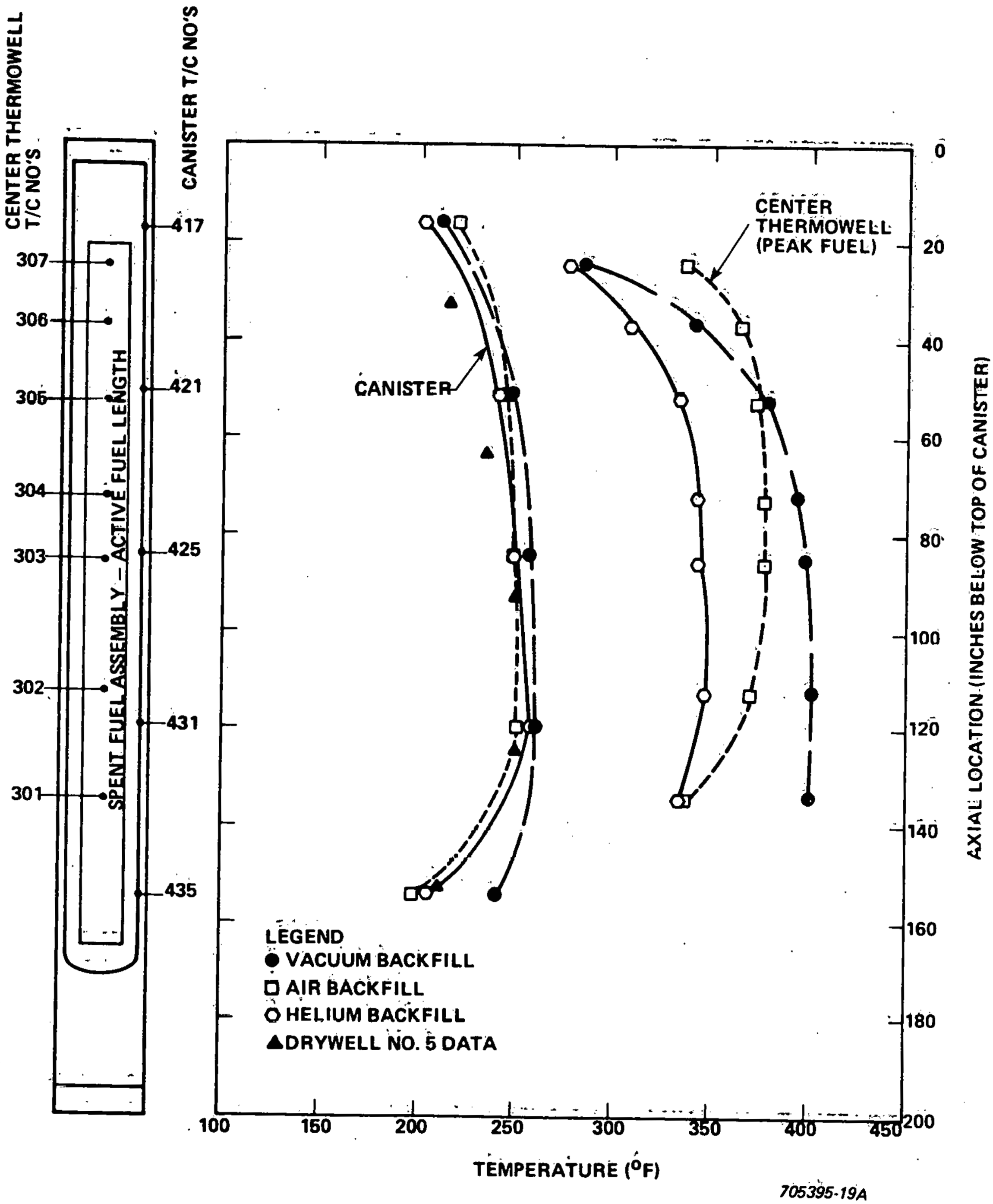


Figure 19. Fuel Temperature Test Profiles for Drywell No. 5 Canister Profile

3.3.5 LAG STORAGE PIT

While the original purpose of the lag storage pit was functional in nature and not experimental, it could no doubt be used for some form of air-cooled vault experimentation. In fact, tests to verify the storage pit's design have already been run and they demonstrate the potential of a passive, air-cooled vault in maintaining satisfactory temperature levels.

The lag storage pit, depicted in Figures 20 and 21, is used to store spent fuel assemblies in canisters prior to final closure welding and during the interval before storage emplacement. The pit is below the Hot Bay floor adjacent to the west wall and has a storage capacity of 24 canisters, arranged in three separate 4 across by 2 deep arrays as shown in Figure 20. The three individual concrete-lined vaults are 22.5 feet deep by 11.7 feet long by 5.7 feet wide, are separated by 29 inch thick concrete walls, and are capped by 46 inch thick concrete top shields. Each top shield contains eight stepped, steel-lined holes for shield plugs which support the canisters containing spent fuel. Within each vault the center to center canister spacing is 36 inches. This spacing is sufficient to preclude criticality under any flooding condition. A steel seismic grid structure is provided in each vault to give lateral support to the canisters under seismic conditions and to assure that spacing will be maintained.

The lag storage pit is designed to be cooled by natural circulation, but fans are provided to enhance cooling. Hot Bay air enters the vaults 21 feet below floor level through nine individual pipes connected to a common 36 inch diameter inlet manifold. This inlet manifold is connected to a 36 inch diameter downcomer at each end of the pit. Air exits the vaults at 5 feet below floor level through nine 18 inch diameter exhaust pipes which terminate 10 feet above floor level. The exhaust ducts have multiple bends to reduce radiation streaming. The pit was designed to accommodate 24 encapsulated fuel assemblies each having a decay heat level of 3 kW.

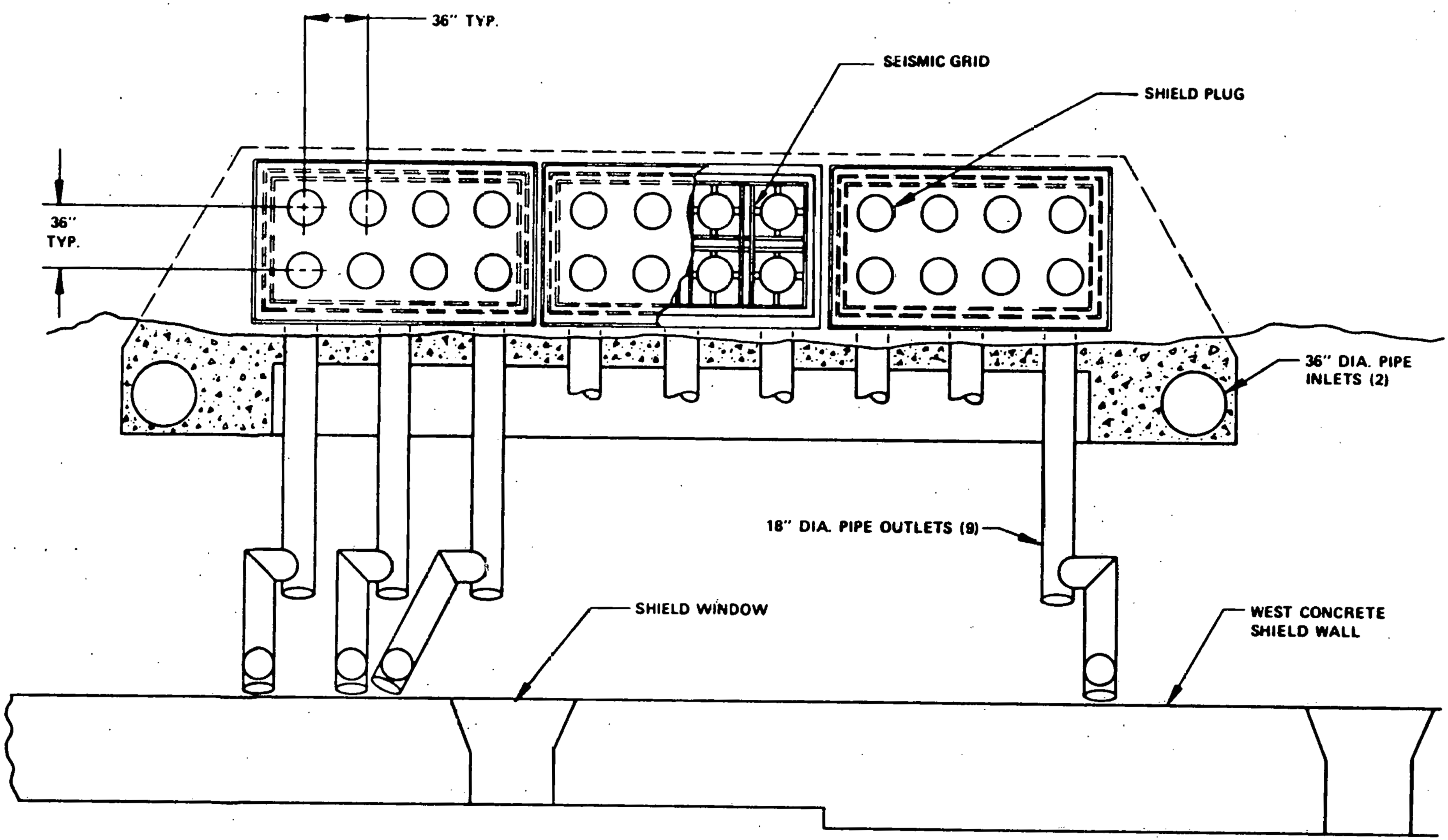


Figure 20. Plan View of Lag Storage Pit in E-MAD Hot Bay

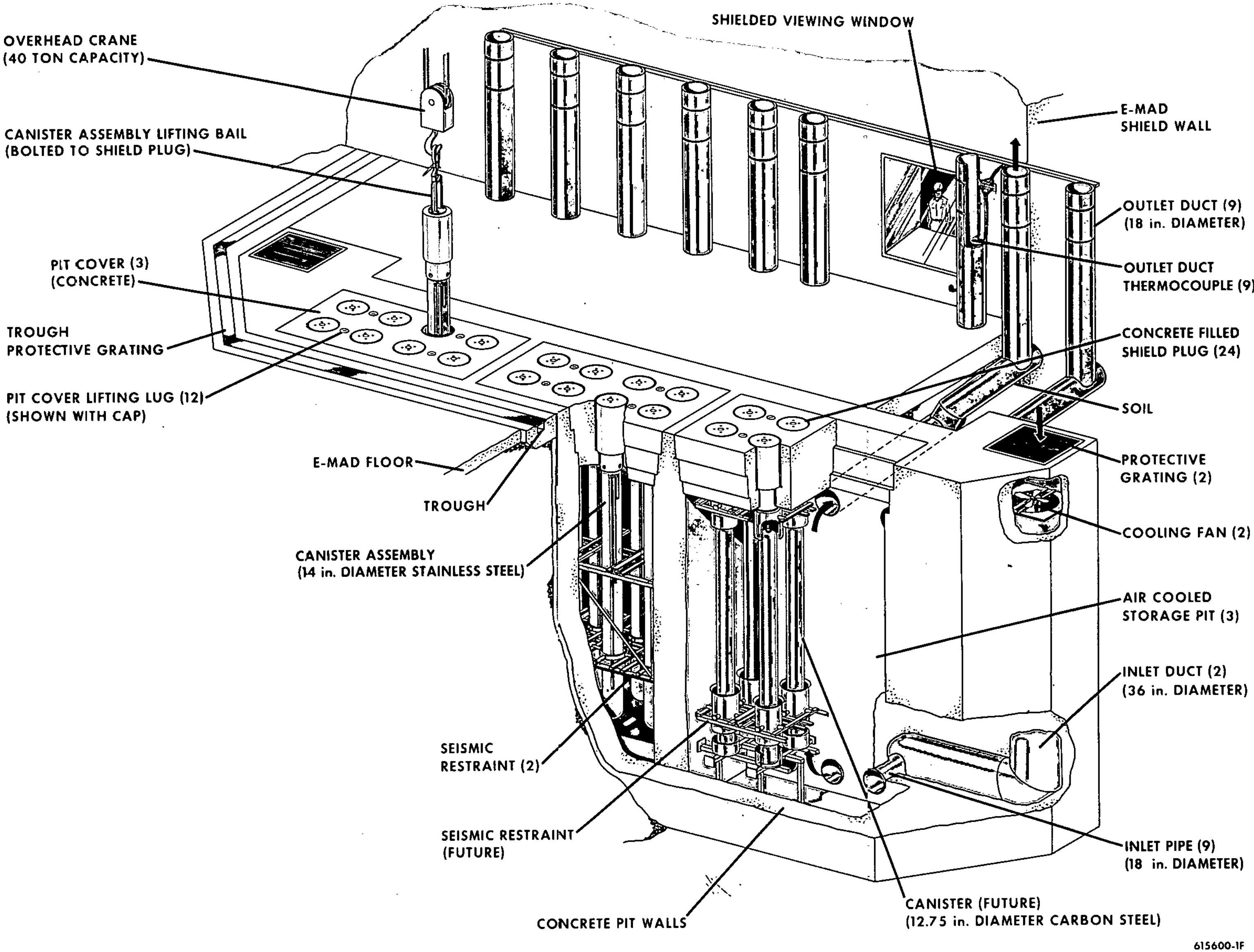


Figure 21. E-MAD Lag Storage Pit

4.0 DRY STORAGE HEAT TRANSFER ANALYSIS

4.1 INTRODUCTION

In the dry storage design process, it is necessary to predict temperatures and temperature distributions in the storage system structure as well as in the stored fuel assembly. Such information is needed in determining drywell spacings, peak fuel temperatures, system transient response, etc. Basically, the procedures needed to perform these predictions are available and an effort to develop new thermal analysis methods in support of the design process is not required. Still, there are important uncertainties in the thermal analysis model. However, they are due not so much to the mechanics of the analysis as to the uncertainties in numerical input for parameters such as emissivities, thermal conductivities and convective heat transfer coefficients. In this section, the dry storage thermal analysis method is reviewed. The review is done on an incremental basis starting with the fuel and working outward towards the heat dissipating medium. Temperature differentials across the various thermal resistances can be compared to aid in identifying those parts of the thermal model to which most attention should be directed.

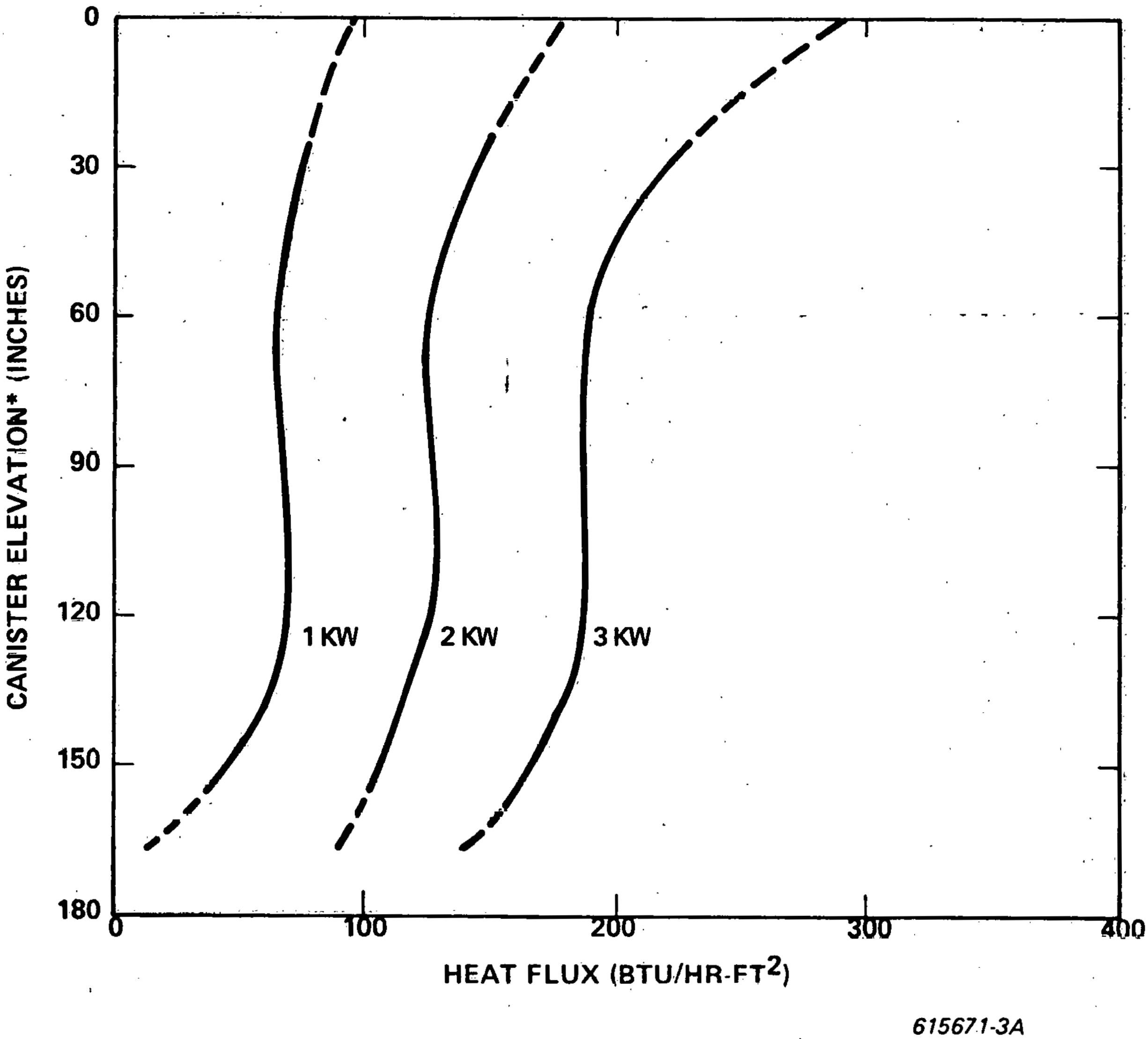
At the present time, the thermal analysis of a dry storage system is performed in two separate parts -- canister external and canister internal. Given a decay heat level and a canister heat flux distribution, the external analysis models the region outside the canister using a finite-difference heat transfer program. The program selected must handle convection, conduction and radiation but a mass flow capability would not be required. The analysis predicts structure temperature distributions, and the resulting canister profile will serve as input to the canister internal model. Using a fuel assembly subchannel program, the internal analysis will result in a new canister heat flux distribution and both analyses, internal and external, can be iterated if necessary. These analyses should be combined and this can probably be done effectively by simplifying one model and retaining all detail in the other depending upon the analysis objective. Thus, if detailed fuel assembly calculations were needed, the internal canister model, with full detail, could be combined with a simplified external model to get the influence of liner and soil into the analysis in one step.

4.2 HEAT TRANSFER PROCESSES

4.2.1 FUEL TO CANISTER

If the canister is evacuated, fuel to canister heat transfer occurs strictly by radiation. However, with gas backfill, the process is more complicated and involves a combination of all three heat transfer modes -- conduction, convection and radiation. With convection present, there is a heat redistribution process. As the gas flows upwards through the fuel assembly due to natural circulation, it picks up heat which elevates its temperature. Near the top of the fuel assembly, the gas temperature can possibly exceed the fuel temperature due to power shape end effects. In that case, a portion of the energy stored in the gas, which originated low in the fuel assembly, will then be convected back to the fuel and on to the canister by convection, conduction and radiation. Thus, when strong convection effects are present, the axial heat flux distribution at the canister side-wall will be skewed towards the top and its shape can differ considerably from the fuel assembly decay heat distribution. This effect was noticed during the analysis of Soil Temperature Test data (Reference 2). The canister is backfilled with air, a good convecting medium, and canister heat flux distributions (Figure 22) show definite heat redistribution. With a lighter gas, such as helium, the tendency to circulate is weaker but the gas thermal conductivity is relatively large. Therefore, heat transfer to the canister would occur primarily by conduction and radiation and the canister heat flux distribution, as found during the Isolated Drywell study, Reference 5, is more cosine-shaped.

Computer programs are available for the subchannel analysis of encapsulated fuel assemblies and the heat transfer/fluid flow processes discussed above are all accounted for. The STAFF-5 program, written by the Hanford Engineering Development Laboratory, and HYDRA-1, a program currently being developed by Battelle Pacific Northwest Laboratory, are examples. Given a canister



*REFERENCED TO CANISTER UPPER END

Figure 22. Canister Axial Heat Flux Distribution Derived From Canister and Liner Temperature Data - Soil Temperature Test

temperature distribution, the programs compute local temperatures (gas and fuel) and gas velocities throughout the fuel assembly and they have the very definite advantage of drawing upon nearly 20 years of subchannel analysis experience in the nuclear industry. Therefore, it is expected that they will accurately represent the canister processes and that ability will be confirmed by comparing calculations with data from the Fuel Temperature Test. This has already been done, on a preliminary basis, with HYDRA-1 during its development. Analysis results are discussed in Reference 4 and comparisons of predicted and measured fuel temperatures are presented in Figures 23 and 24. More work of this type is needed to develop further confidence in the programs and it would also aid in identifying appropriate values for emissivities, convective heat transfer coefficients, and other numerical input. Once this step is accomplished, a program could then be applied in the dry storage design process to a range of independent variables (decay heat level, backfill medium, canister temperature) and to various fuel assembly designs. Potentially, the program could also reduce the demand for expensive tests of the FTT type.

4.2.2 CANISTER TO LINER

Heat transfer across air filled spaces is modeled considering radiation and a combination of conduction and convection. Radiation is included in the analysis by supplying shape factors that depend upon emissivities and the areas of the radiating surfaces. For convection and conduction, correlations are available that allow both heat transfer modes to be handled in a single calculation. Between the canister and liner, for example, convection and conduction can be simulated using the "effective conductivity" method described in Reference 8 (pages 330, 331). For an annulus thickness of 1.625 inches and a temperature differential of 50°F, for example, the effective thermal conductivity is 1.5 to 3 times larger than the conductivity of air at temperatures between 200°F and 600°F. As the annulus narrows, convection is suppressed, conduction becomes more dominant, and the correlation reduces to air's thermal conductivity.

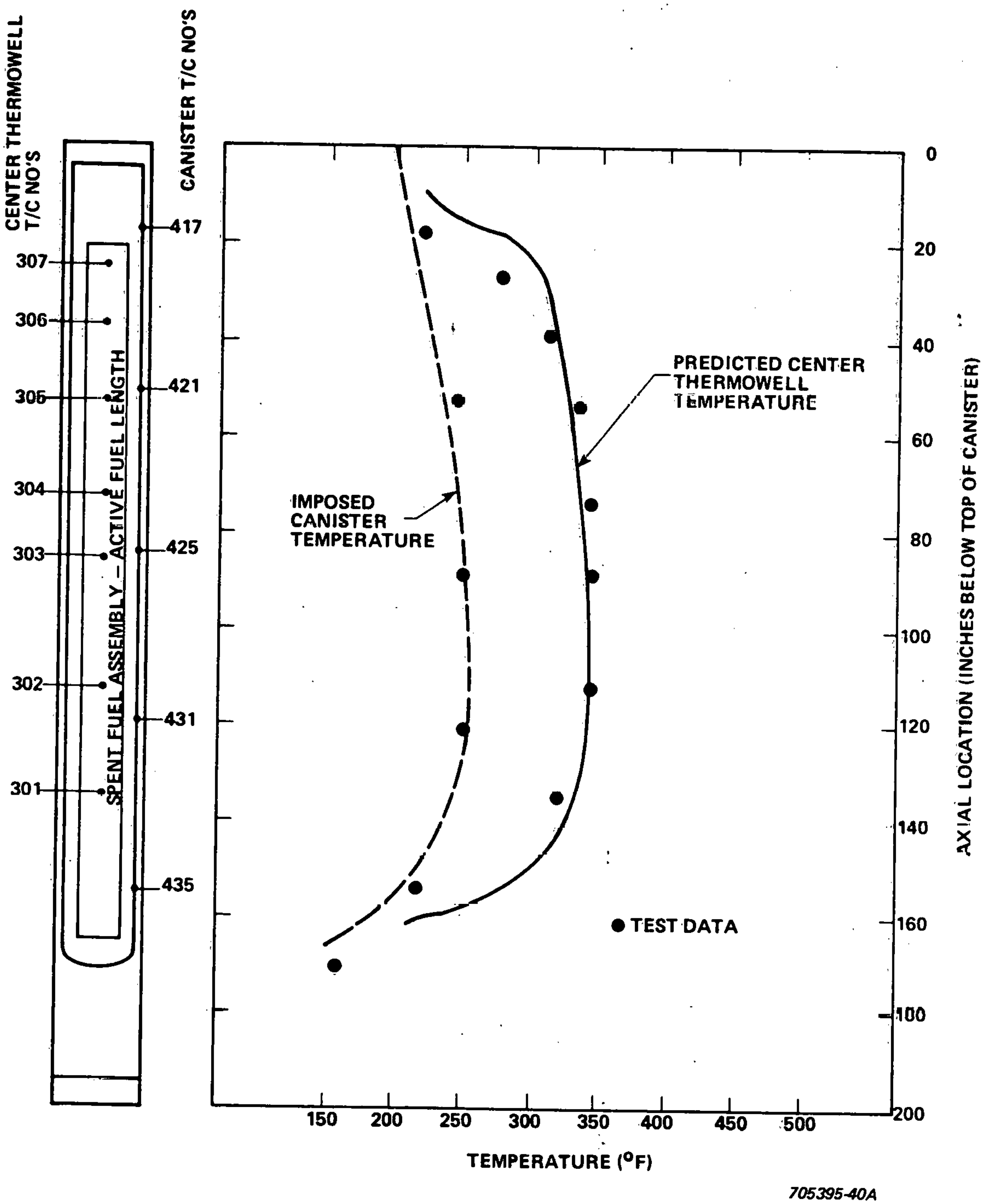


Figure 23. Predicted Fuel Temperatures and Test Data for the Helium Filled Drywell Canister (0.85 kW) - Fuel Temperature Test

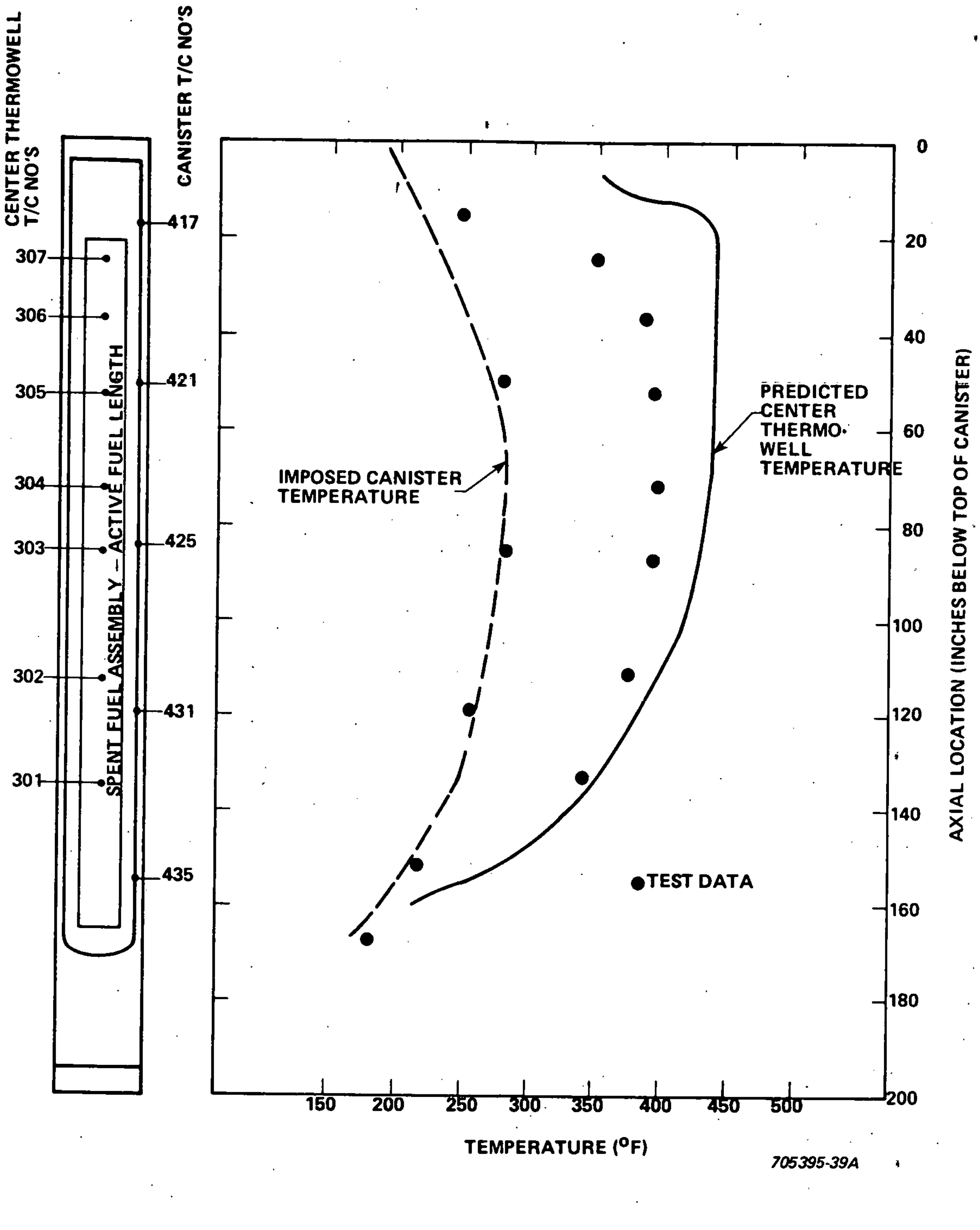


Figure 24. Predicted Fuel Temperatures and Test Data for the Air Filled Drywell Canister (0.85 kW) - Fuel Temperature Test

Heat transfer from the canister's lower end can probably be handled assuming air stratification at that location. Thus, convection effects would be neglected and conduction, in addition to radiation, would control. At the upper end, convection will be much more significant and a correlation such as that provided in Reference 9 (page 182, Eq. 7-9d) could be used to approximate the convection/conduction heat transfer coefficient. It is noted that for most analyses, a large amount of effort should not be spent in developing canister end-effect models. Typically, heat transfer rates at each end will be less than 2% of the total. Therefore, inaccuracies can be afforded in those models without having a serious impact on results.

4.2.3 LINER TO SOIL

In the analysis of near-surface drywells, the major resistance to heat transfer will be provided by the surrounding soil. Therefore, a soil thermal conductivity model must be available. The conductivity will vary, of course, with soil composition. This is easily determined and, once it is known, published information on soil thermal properties can be consulted. However, the conductivity also depends strongly upon moisture content and this complicates the problem since moisture levels are variable and will change with season and also as a result of the drying action provided by heat from the stored fuel assembly. Evidence of soil drying was observed during the analysis of data from Isolated Drywell Tests, Reference 5. It was noted that the temperature differential between points on the liner and in the soil 5 feet away (both points at the same depth) remained virtually constant during 19 months of testing and data collection. However, during the same time, the decay heat level decreased from 1.1 to 0.65 kW -- a reduction of 40%. The most plausible way a declining heat transfer rate can support a nearly fixed temperature differential is if the soil's thermal conductivity also declined by 40% during the same period. Thermal conductivity predictions for high sand-content soil are presented in Figure 25. The predictions are from a correlation, Reference 10, that provides a good representation of E-MAD soil conductivity. This judgment is based upon actual dry soil data (K = 0.3 Btu/hr-ft-F) obtained at E-MAD and upon the low temperature (< 160°F) conductivity values (0.6 - 0.9 Btu/hr-ft-F) required for accurate soil

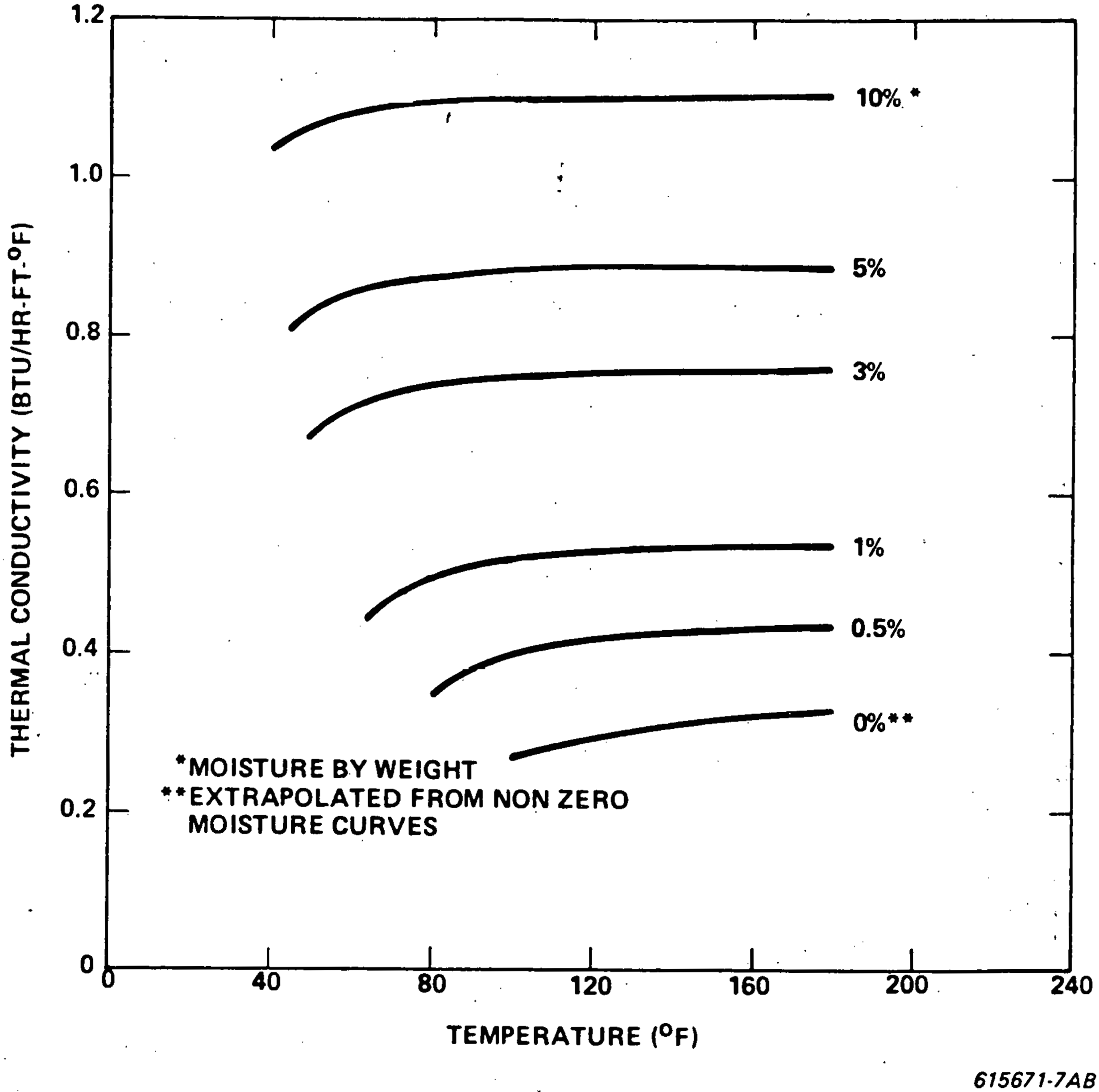


Figure 25. E-MAD Soil Thermal Conductivity Predictions - Based Upon Reference 10 Correlation

temperature predictions. The moisture content of E-MAD soil between the 5 and 20 foot depths, before heat addition, is typically 5%. Thus, a 40% conductivity reduction could reflect a decrease in moisture content from 5 to approximately 2% and the possibility of such drying, especially in the near-field zone, is reasonable.

To consider the thermal conductivity of soil in a thermal analysis, the dry soil value could be used but this would result in undue conservatism. At 1.0 kW, reducing the soil thermal conductivity from 0.5 to 0.25 Btu/hr-ft-F, for example, will increase the peak canister temperature by 100°F. A more reasonable approach is to observe near-field soil drying through the analysis of soil temperature data from operating drywell tests. Those data can be applied, as in the Isolated Drywell Test analysis, Reference 5, to derive a time-dependent conductivity curve normalized to the initial moist soil conductivity. A third approach involves the development of a soil moisture model. However, this would require considerable effort and should be undertaken only after other approaches have been tried.

4.2.4 GROUND TO AMBIENT

The Soil Temperature Test analysis, reported in Reference 2, considered solar effects at ground level as well as convection to and from the ambient air. Further work has confirmed, however, that the ground level model can be simplified, with satisfactory results, by equating air and surface temperatures and ignoring the solar effects. Using monthly air temperature averages taken from E-MAD site weather data, this method was applied to the Isolated Drywell analysis, Reference 5. The resulting soil temperature predictions agreed well with test data in terms of both magnitude and seasonal time response.

4.2.5 DRYWELL TEMPERATURE SUMMARY

Peak temperature data for isolated 1 and 2 kW drywells are summarized in Table 1. The temperatures are derived from FTT information appearing in Figure 17 and from Soil Temperature Test data plotted in Figure 8. The differentials between temperatures confirm the importance of the soil thermal model. The second most important calculation pertains to the temperature differential between fuel and canister. Other parts of the model are not so critical. However, the canister/liner calculation should continue using the "effective conductivity" method in addition to radiation. This will keep the model general which will be of value when parameters such as canister/liner spacing, power level and the temperature level are varied over wide ranges.

4.3 THERMAL ANALYSIS DEVELOPMENT AREAS

Based upon the proceeding discussion, it is evident the development of dry storage thermal analysis methods should continue in the soil model and internal canister areas. Regarding the soil model, a reliable method for representing thermal conductivity and the effects of moisture and drying should be developed. As a first step, all soil temperature data collected at E-MAD during the Soil Temperature and Isolated Drywell Tests should be analyzed for evidence of soil drying. Based upon observed changes in temperature differentials with time, it may be possible to normalize instantaneous conductivities back to the initial moist soil value. Such a relationship between conductivity and time could then be applied to analyses in the near-field soil zone and it would be updated as needed as further drywell data become available. The fact that data from the Soil Temperature and Isolated Drywell Tests are currently being stored on computer file will provide for an efficient data analysis and one that is able to access and use all test data.

As part of this effort, consideration should also be given to procedures for characterizing the thermal conductivity of other soils with minimum experimentation. Such procedures would find usefulness in assessing the suitability of other sites and soils for dry storage.

Work should also be undertaken to develop a subchannel analysis model using a computer program such as STAFF-5 or HYDRA-1. This is definitely needed to gain an improved understanding of the heat transfer/fluid flow process occurring within the canister and of the effect that various parameters have on fuel temperatures. Once the model is developed, it will be qualified using data from the Fuel Temperature Test and passive heat dissipation tests. The qualification procedure would be planned to develop maximum confidence in the model's ability to analyze other stored fuel assemblies and fuel assembly designs.

TABLE 1: SUMMARY OF ISOLATED DRYWELL TEMPERATURES

	DECAY HEAT LEVEL	
	1 kW	2 kW
Peak Fuel Temperature (° F)*	375	575
Canister Temperature (° F)**	275	475
Liner Temperature (° F)**	225	425
Grout Temperature (° F)**	215	400
Ambient Soil Temperature (° F)**	70	70

*Based on FTT data, Figure 17, with helium backfill.
**Soil Temperature Test data, Figure 8.

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