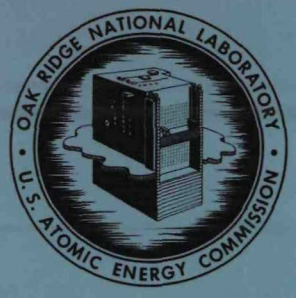

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HEALTH PHYSICS DIVISION

CHEMICAL TECHNOLOGY DIVISION

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DEMONSTRATION DISPOSAL OF HIGH-LEVEL RADIOACTIVE SOLIDS IN LYONS, KANSAS, SALT MINE: BACKGROUND AND PRELIMINARY DESIGN OF EXPERIMENTAL ASPECTS

R. L. Bradshaw,[a] J. J. Perona,[b] and J. O. Blomeke[b]

Abstract

A demonstration of the disposal of high-level radioactive waste solids to be carried out in a salt mine at Lyons, Kansas, will have as its objectives: (1) the demonstration of required waste-handling equipment and techniques, (2) the determination of the stability of salt under the influence of heat and radiation, and (3) the collection of information on creep and plastic flow of salt which is needed for the design of an actual disposal facility.

As presently conceived, 14 irradiated fuel assemblies from the Engineering Test Reactor will serve as a source of radiation in lieu of actual solidified wastes. The assemblies will be placed in a circular array of holes in the floor with one can in the center and other six cans located peripherally, spaced 5 ft on centers. During the course of the 2-year test, four sets of assemblies will be used to achieve a peak dose to the salt of about 8×10^8 rad and the temperature of the adjacent salt will be maintained at 200°C with electrical heaters. A second array, consisting only of heaters, will be operated as a control to determine those effects due solely to heat.

In addition to the radioactive and control arrays, a rib-pillar located between the two arrays will be heated electrically around its base to produce significant information on salt flow characteristics at elevated temperatures.

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1. Introduction

Because of safety considerations, the conversion of high-level wastes to solids and their subsequent disposal is regarded as a matter of paramount long-range importance to the development of nuclear power. Pot calcination, a comparatively simple process, currently under development at ORNL and Hanford, is the solids conversion route currently favored by the Laboratory. Rock salt is regarded as the optimum disposal medium for high-level waste solids.

In the spring of 1962, the Division of Reactor Development of the AEC requested that a study be made of the feasibility of using irradiated fuel elements to simulate solidified high-level radioactive waste storage in salt formations. This study led to the general conclusion that it was feasible to use irradiated fuel elements to establish the practicality of using salt for waste disposal by the time significant quantities of calcined wastes would be produced.

As a result of a review of the scope of the demonstration as conceived in the feasibility study, it was concluded that, for a relatively small additional cost, the scope could be extended to yield additional information which would be valuable in the design of an actual disposal facility. After further discussions with Laboratory management and AEC officials, it was decided to extend the scope to include design and fabrication of prototype waste-handling equipment and to obtain additional information on the effect of elevated temperatures on the creep and plastic flow of salt.

This report presents the background considerations and calculations of heat transfer, radiation dosage, and plastic flow which have served to define many of the experimental aspects of the demonstration. Although the authors of this report have had the primary responsibility for this phase of the work, all individuals in the "disposal-in-salt" program have contributed to the conceptual design and participated in all major decisions. These individuals are W. J. Boegly, Jr., F. M. Empson, H. Kubota, F. L. Parker, W. F. Schaffer, Jr., and E. G. Struxness.

2. Objectives and General Description of Demonstration

The engineering and scientific objectives of the demonstration are: (1) demonstration of waste-handling equipment and techniques; (2) determination of possible gross effects of radiation (up to 10^9 rad) on hole closure, floor uplift, salt-shattering temperature, etc., in an area where salt temperatures are in the range of 100° to 200°C; (3) determination of possible radiolytic production of chlorine; and (4) collection of information on creep and plastic flow of salt at elevated temperatures which can be used later in the design of an actual disposal facility.

The demonstration will be carried out in the Lyons, Kansas, mine of The Carey Salt Company with 14 irradiated Engineering Test Reactor (ETR) fuel assemblies contained in seven cans. These cans will be placed in a circular array of holes in the floor with one can in the center and the other six cans located peripherally on 5-foot centers. To increase the radiation dose received by the salt, the assemblies will be exchanged for freshly irradiated assemblies at 6-month intervals over the course of 2 years. All fuel assemblies will be returned to the Idaho Chemical Processing Plant (ICPP) for recovery of the unfissioned fuel.

An identical array with only electrical heaters will be operated as a control to determine the combined effect of radiation and heat on the salt characteristics. In addition, one rib-pillar will be heated by a number of electrical heaters placed in the floor around its base to yield information on the creep and plastic flow of salt at elevated temperatures.

A schematic cross section of the demonstration is shown in Fig. 1, and the plot plan of the demonstration site is shown in Fig. 2. As presently conceived, the assemblies, after canning in Idaho, would be shipped by rail in an existing cask, especially modified for this purpose. At Lyons, the cask would be removed from a rail car standing on an existing spur, and up-ended over a cased, vertical shaft extending to the mine working area, approximately 1000 ft below. The assemblies would be lowered, one at a time, through the shaft and into a movable shielded cask mounted on a fuel assembly transporter. The transporter would move to the experimental area where the cask would be positioned and lowered

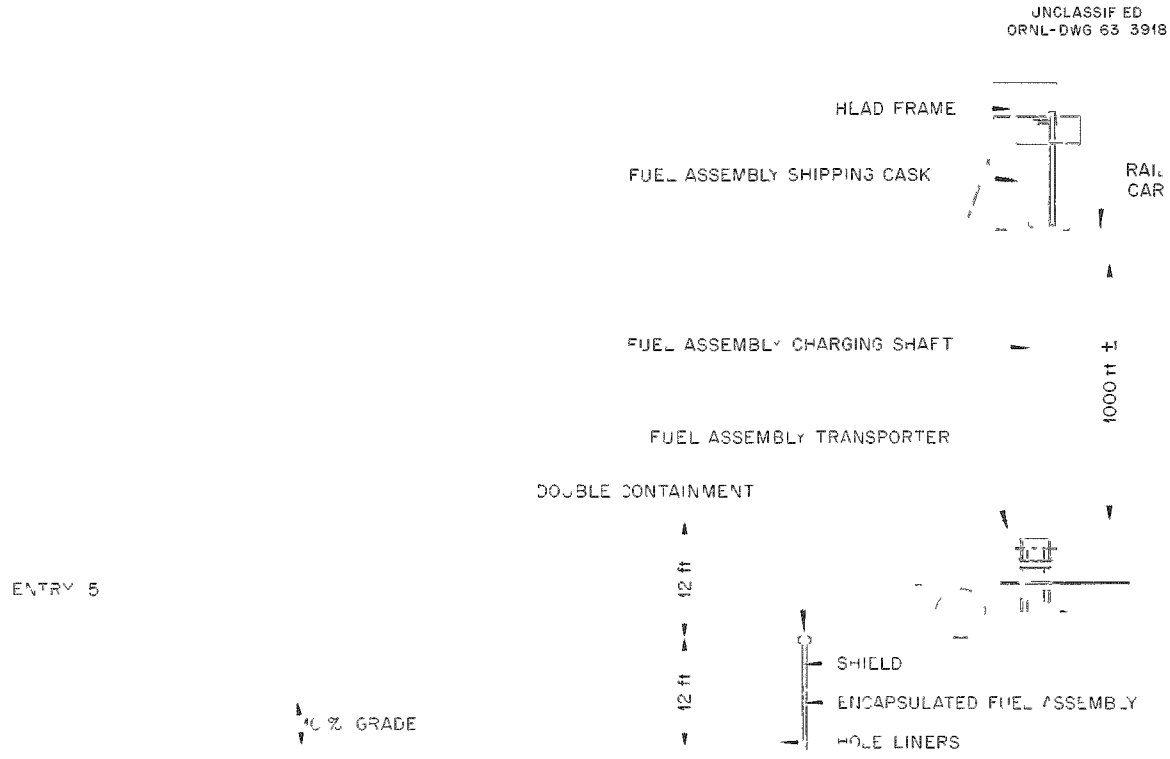

Fig. 1. Schematic Cross Section of Demonstration.

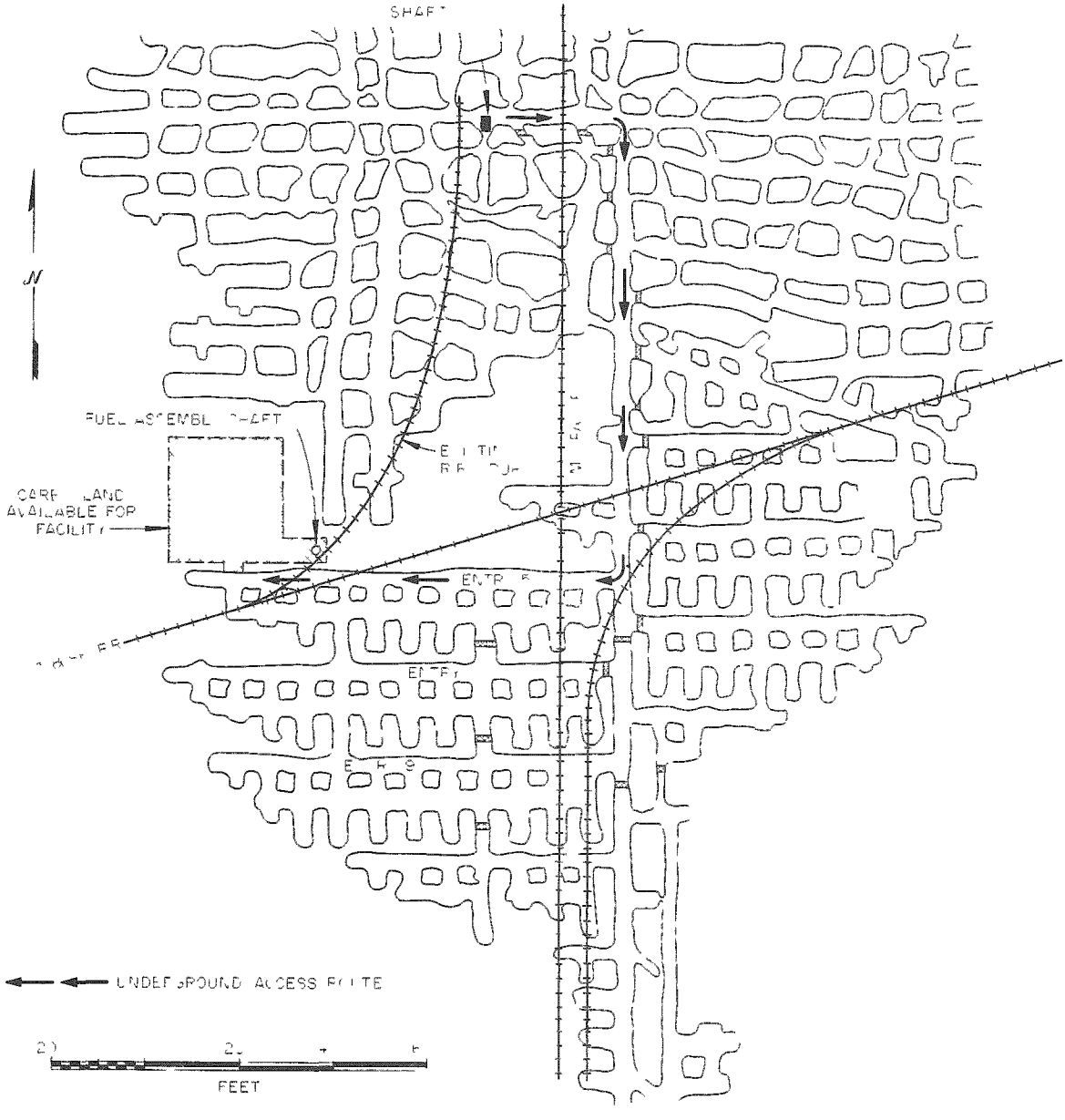

Fig. 2. Demonstration Site in Newly Mined Area, Lyons, Kansas.

over the designated hole in the floor of the mine. The can would then be lowered through the bottom of the cask into place. The holes, approximately 10 in. in diameter by 12 ft deep, would have suitable liners. Lead or uranium shields placed in the top of the holes would serve as biological shielding while the cans were in place.

To meet the objectives of the experiment, it is necessary to expose a reasonably large mass of salt to radiation dosages and temperatures comparable to those anticipated in an actual disposal operation. The particular geometrical configuration chosen for this experiment would expose a circular area about 12 to 14 ft in diameter to the desired temperatures and radiation dosages. The 5-ft spacing is about as small as will likely be used in an actual disposal operation, and the dose midway between any two containers will be due almost entirely to those two containers. An outer ring of twelve additional cans would, of course, increase the area affected; however, the benefits to be gained from a larger test are not believed to justify the added expense and complexity.

3. Selection of the Mine

Several alternative sites considered for the operation of the demonstration were the Project Gnome site in New Mexico, the Hutchinson Naval Air Station, and The Carey Salt Company's Hutchinson mine.

The Hutchinson mine was ruled out by the Carey Company. The Naval Air Station was ruled out by the fact that the use of this site would require the development of a complete mine installation, including a shaft and hoisting equipment.

The Gnome site has the advantages of being located on Government-owned land having mine space available for immediate use. The disadvantages of the Gnome site are the very poor quality of the salt, so that it would not be representative of the salt formations which most likely will be used as a permanent facility, its inconvenience with regard to transportation facilities, and possible conflicts in schedule with the Plowshare group. The remoteness of the Gnome site is both an advantage and a disadvantage.

The Lyons mine has the advantages of location, rail connections, and favorable public relations background at both state and local levels.

4. Radiation Source Selection

The decision to use irradiated reactor fuel assemblies in this experiment, rather than actual calcined wastes or separated fission-product sources was based on considerations of availability, cost, and radiation characteristics. Selection of the ETR fuel was made from considerations of the operating cycle of the reactor, the number of assemblies which would be required to charge seven holes in the demonstration, and the dimensions of the assemblies. From the standpoint of allowable element temperature, power reactor elements would have been preferable, but uncertainties in availability led to the selection of the ETR fuel assembly as the best over-all choice.

The fluidized bed waste calciner facility (WCF) at the National Reactor Testing Station (NRTS) was considered as a source of waste for the test but was ruled out. Operation of the WCF with radioactive waste is expected to begin the latter part of 1963, and possibly by the end of 1964 the systems could have been debugged and flushed out with the hottest waste (200-day decayed) which the plant is designed to handle. By the time the waste could be canned and placed in the mine, it would be about 1 year decayed. A 6-in. by 6-ft-long cylinder of WCF waste would have a heat-generation rate of about 140 watts at 1 year's decay and 41 watts at 2 years' decay. This compares with 750 watts at 90 days and 74 watts at 1 1/4 years for two ETR assemblies in a 5-in. cylinder, about 7 ft long. In addition to the fact that the WCF waste would result in lower dose rates than ETR assemblies, there is no hot-cell facility available at the WCF to fill the cans.

Cylinders of solidified waste from the pilot plant at Hanford were ruled out, primarily on the basis of the currently projected schedule. It seems probable that the first seven pots will not have been produced before January 1967, and these pots might not be available for experimental storage in any event. The heat-generation rate of a 6-in. pot filled to a level of 6 ft would be expected to be about 810 watts at 1 year's decay and 260 watts at 2 years' decay.

Of the power reactor fuel assemblies, the Yankee Atomic appeared to be the most favorable, except for its dimensions. The over-all assembly dimensions are about 11 in. across the diagonal by 12 ft long. The heat-generation rate of an assembly would be about 1070 watts at 6 months' decay (about the earliest that it could be canned and moved to the mine), 470 watts at 1 year, and 175 watts at 2 years. However, the uncertainty of availability of enough assemblies to fill seven cans from any given power reactor within any given time period, coupled with the fact that hot-cell facilities for canning are not generally available at the reactor, led to the elimination of power reactors.

The use of various isotopes was ruled out on the basis that they did not appear to offer any appreciable cost advantages, and they have the disadvantage of not presenting the wide gamma energy spectrum which would be obtained with fuel assemblies. For example, to obtain the same peak gamma dose to the salt as would be obtained from the ETR assemblies (assuming three changeouts during the 2-year period) would require about 200,000 curies of Co^{60}. The projected inventory price (the price to AEC users) of Co^{60} by the end of 1964 is expected to be about 40 to 60 cents per curie, or about $100,000 for 200,000 curies.[1] However, as the design of the handling equipment and fuel assembly containers has proceeded, it has become apparent that there may be a number of problems incidental to use of the assemblies which might be simplified or eliminated by the use of Co^{60}. Consequently, Co^{60} is considered as a possibly attractive alternative, should later complications in the use of fuel assemblies develop.

The ETR has an average thermal flux of about 1.5×10^{14} and a cycle time of about 6 weeks. A typical reactor cycle might average about 20 full-power days out of 23 operating days, followed by a 1- to 3-week shutdown for reloading, etc. Thus, it is possible to obtain assemblies at almost any time desired. The dimensions of the assembly are also convenient (3 in. square by 36 in. long), and the only major disadvantage (one which it shares with most test reactors) is that it is a relatively low-melting, aluminum-base fuel.

If the assembly temperature is to be kept below 900°F (M.P. aluminum, 1220°F), the earliest that the assembly can be canned is about 60 days

as explained further in Section 5. This means that it will be 90 days' decayed before it is placed in the salt mine.

5. Calculation of Fuel Assembly Temperatures

5.1 In the Hot Cell

The system consists of two ETR fuel assemblies in a stainless steel, 5-in.-OD pipe, sealed at the ends. The heat generated in the fuel is transmitted to the pipe wall and then to the ambient air in the hot cell. The heat flux through the pipe surface as a function of time since reactor discharge is as follows:

Time (days)	Flux (Btu hr^{-1} ft^{-2})
7	3250
20	1610
45	737
90	325

These fluxes were obtained using the heat-generation rate curve in Fig. 3. (For comparison purposes, a heat-generation curve is also shown for a hypothetical 6-in. acid Purex calciner pot ca. 1975.) Fuel assembly temperatures vary from 1740°F at 7 days to 650°F at 90 days (Fig. 4). The earliest age for canning with a reasonable margin of safety appears to be about 60 days, when the fuel assembly temperature would reach 850°F and the can surface 300°F.

Can temperatures were calculated using combined convection and radiation heat transfer coefficients for steel pipe obtained from Table 7-2, page 179, in Heat Transmission by W. H. McAdams, 2d edition. Combined coefficients ranged from 5.70 to 2.35 Btu hr^{-1} ft^{-2} $°F^{-1}$ as the pipe temperatures varied from 665°F to 220°F.

Temperature differences between the fuel assembly surface and the can wall were calculated using emissivities of 0.1 for the aluminum fuel assembly and 0.55 for the stainless steel can, which gave an $\mathcal{F}$-factor of 0.095. Convection coefficients for the enclosed air layer were calculated from Fig. 25-7, page 538, in Heat Transfer by M. Jakob, where the ratio

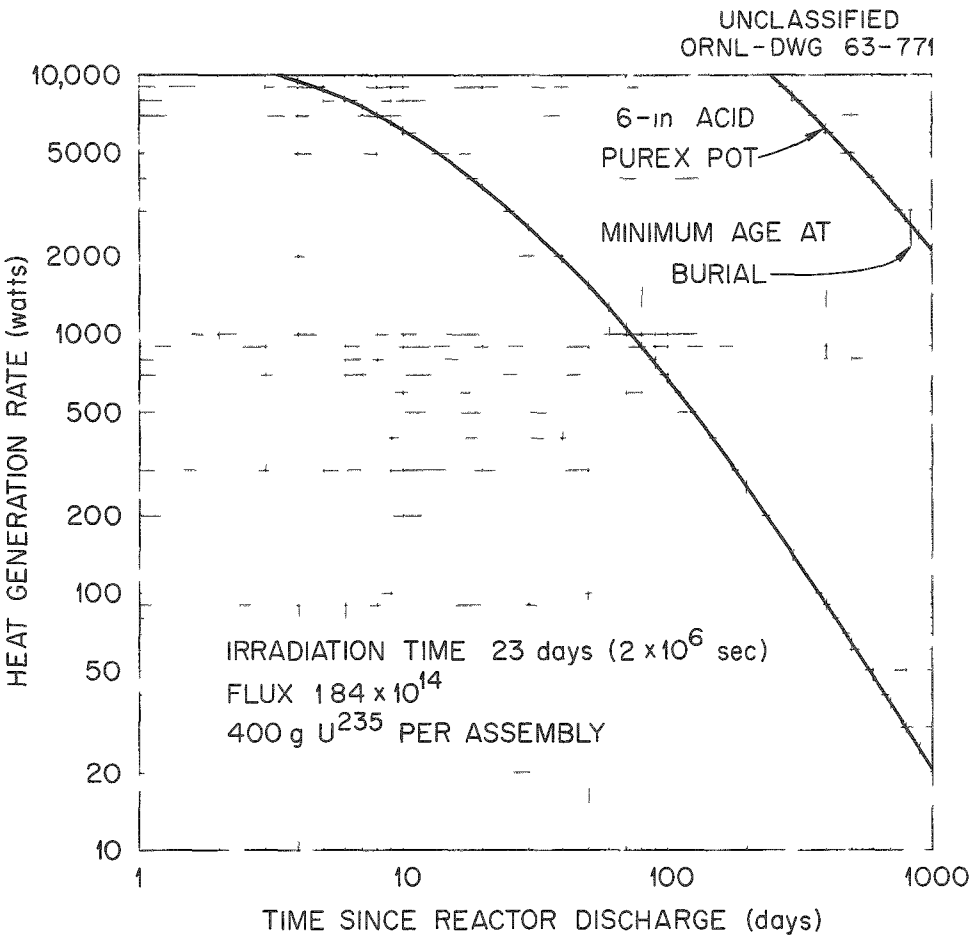

Fig. 3. Heat Generation for Stack of Two ETR Assemblies.

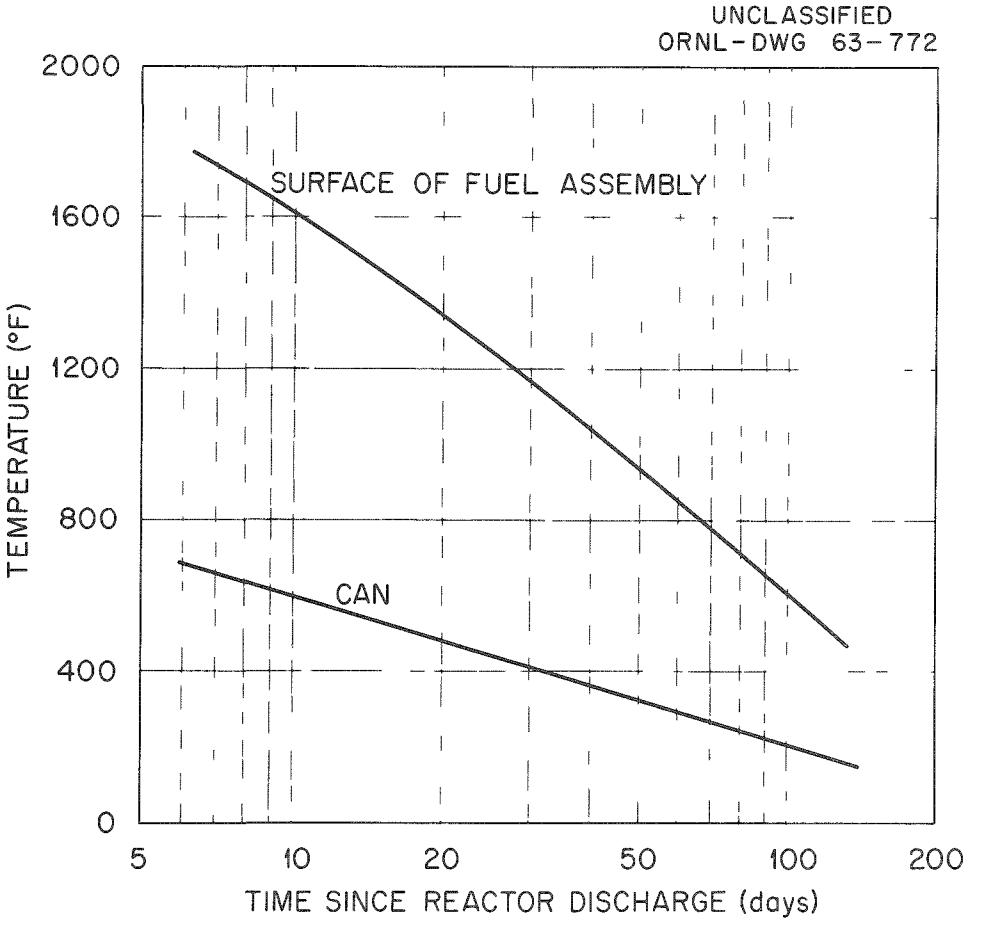

Fig. 4. ETR Fuel Assembly Temperatures in Hot Cell.

of a combined convection and conduction coefficient to the conduction coefficient is plotted as a function of the Grashof number. Heat fluxes between the fuel assembly and the can (based on the fuel assembly surface area of 3.0 ft^2) are listed as follow:

Time Since Reactor Discharge (days)	Fuel Assembly Temperature (^oF)	Radiant Heat Flux (Btu hr^{-1} ft^{-2})	Convection and Conduction Flux (Btu hr^{-1} ft^{-2})
7	1740	3530	724
20	1350	1590	520
45	970	609	351
90	650	218	207

Temperature gradients through the fuel assembly will be negligible (on the order of 10^oF difference between interior and exterior plates), because of the excellent thermal conductivity and adequate cross-sectional area available for conduction to the side plates.

5.2 In the Shipping Cask

If the first fuel assembly is canned at 60 days, the seven cans may be ready for shipping at 75 days after reactor discharge. The system now consists of a canned fuel assembly in a tube surrounded by water at 100^oF. (The shipping cask will be water-cooled with forced circulation.) The gap between the can wall and the cask tube wall will be about 1/4 in. Both the can and tube are stainless steel with emissivities of 0.55, giving an $\mathcal{F}$-factor for radiant heat transfer of 0.38. Conduction, convection, and radiation were taken into account through this second air gap using the same methods as before. The calculated temperatures were:

	Temperature (^oF)	Radiant Flux (Btu hr^{-1} ft^{-2})	Convection and Conduction Flux (Btu hr^{-1} ft^{-2})
Cask Tube	100	---	---
Can	345	200	213
Fuel Assembly Surface	810	352	189

At 75 days the heat generated in the cask from the 14 fuel assemblies would be about 22,600 Btu/hr. If the water coolant would undergo a 20^oF temperature rise in passing through the cask, a flow rate of

2.2 gpm would be sufficient. The water inventory in the cask would weigh about 200 lb and the lead about 20 tons, so that if circulation stopped, the water would be heated to the boiling point in about 2 to 4 hr, and about 10 hr would be required to evaporate the water.

5.3 In the Salt Mine

The shielding for the transporter in the mine may be made of lead shot, resulting in a shield with a thermal conductivity poorer by a factor of 75 than solid lead (Fig. 11-7, page 290, in Heat Transmission by W. H. McAdams, 3d edition). Although the heat capacity of the cask will prevent melting of the lead for 10 to 20 hr, a cooling system should probably be provided for the transporter.

The fuel assembly can will be lowered into a hole in the floor of the mine containing a second or outer can to keep the salt from freezing the inner can in the hole. The outer can (here assumed to be stainless steel) will have heaters attached to permit more heat to be transferred to the salt than is given off by the fuel. The outer can was assumed to have an outside diameter of 6.25 in. and the hole in salt, a diameter of 10 in.

If the shipping cask is loaded at 75 days, the cylinders may be in place in the mine at 90 days after reactor discharge. The emissivity of the salt was taken to be 0.9, giving an $\mathcal{F}$-factor for the last air gap of 0.41. Calculated temperatures and heat fluxes, assuming 1600 w total heat-generation rate per can (both decay and electrical heat), were as follow:

	Temperature ($^{\circ}$F)	Radiant Flux (Btu hr^{-1} ft^{-2})	Convection and Conduction Flux (Btu hr^{-1} ft^{-2})
Salt	400 (assumed)	312	36
Outer Can	540	---	---
Inner Can	625	258	67
Fuel Assembly Surfaces	875	295	132

It thus appears that the fuel assemblies may be canned at 60 days' decay, shipped at 75 days, and placed in the mine at 90 days without exceeding a temperature of 900°F in the assembly.

6. Salt Dose Calculations

The final salt-dose calculations cannot be made until the irradiation history of the actual assemblies is known; but, based on preliminary calculations, it appears that the peak salt dose with two 90-day-decayed ETR assemblies in a can will be about 3×10^8 rad, accumulated over a 2-year period. Since laboratory tests have indicated little change in physical properties at 10^8 rad, but a significant (about 10%) drop in compressive strength at 5×10^8 rad, it would be desirable to achieve doses near 10^9 rad in this experiment, if practical. Changing the assemblies three times during the course of the 2-year test (four sets of assemblies, total) should increase the peak dose to about 8×10^8 rad. At the same time, this will give additional experience with the operation of the handling equipment.

These preliminary calculations were made with a shielding code on an IBM-7090 computer.[2] No mass-attenuation coefficients, energy-absorption coefficients, or build-up factors are available for salt; but, since its density (135 lb/ft^3) is about the same as that of concrete, it is believed that the shielding and energy absorption properties will be about the same as for concrete. Thus, concrete was assumed as the media in the dose calculations. The shielding code also gave dose rates in units of rem/hr; but, since the energy absorption coefficients in tissue for gamma energies from 0.15 to 3 Mev are within 10% of those for concrete, it is believed that the calculations are sufficiently accurate.

Figure 5 shows the salt dose to be expected during the 2-year period from the ETR assemblies if placed in the mine after 90 days' decay (curve A) and from changeout of four sets of 90-day-decayed assemblies (curve B). Shown for comparison is the dose which might be expected from a 6-in.-diam by 10-ft-long pot calciner cylinder containing a hypothetical acid Purex waste of the future (ca. 1975). Curve C is the dose which would be accumulated in a 2-year period following burial at the earliest possible age (2.3 years). Curve D shows the dose which would accumulate over a period of 286 years. (After 300 years, little additional dose would accumulate.) It should be pointed out that the assumed Purex waste is from high burnup fuel (10,000 Mwd per metric ton of 2% enriched uranium, or 50% burnup of

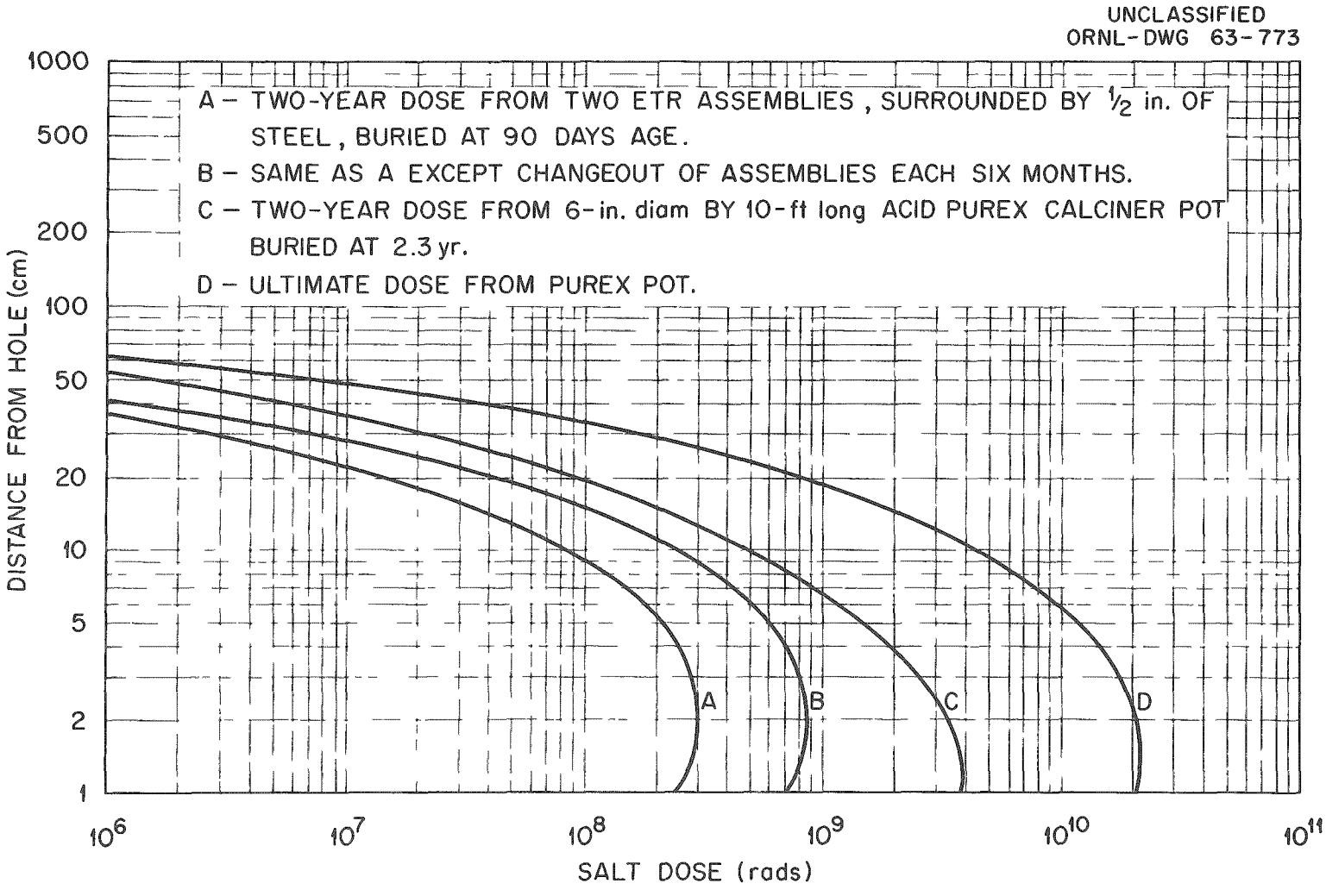

Fig. 5. Dose to Salt from ETR Assemblies and Acid Purex Calciner Pot.

the U^{235}) and is considerably "hotter" than any currently being produced. (The calciner cylinder would contain about 15 kg of fission products, while the two ETR assemblies, with about 15% burnup of 93% enriched uranium, will only contain about 0.12 kg.) The hypothetical Purex pot at 2 years' decay is about an order of magnitude hotter than is anticipated in a 2-year-decayed pot from the ORNL pot calciner pilot plant at Hanford.

From curve B in Fig. 5, it may be seen that, at distances of more than a foot from the fuel assembly cans, the salt dose accumulated over the 2-year period will be less than 10^7 rad. Since the cans are spaced 5 ft on centers, the contributions from the other six cans to the dose near any one can will be negligible. Isodose surfaces in the regions of accumulated dose greater than 10^6 rad are thus essentially circular cylinders around the individual fuel assembly cans.

Calculations for a 50-ft-wide room full of 6-in.-diam calciner pots of acid Purex waste, spaced 5 ft on centers, have indicated that the dose in air at the center of the room will be less than 0.3 mr/hr if there is 6 ft of solid salt above the pots. Thus, with the fuel assemblies (which are less radioactive), it will only be necessary to provide shielding in and near the top of the holes to keep personnel exposure levels within satisfactory limits.

7. Experimental Layout in Mine

7.1 Consideration of Use of Existing Mine Space

From the standpoint of the economics of an actual disposal operation in an abandoned mine, it would probably be cheaper to use existing mine space for the disposal of the waste, rather than using it to store excess salt, provided it could be shown that the use of existing space for disposal did not significantly reduce the safety of the operation. At this time it is not possible to predict the structural safety of a mine in general, or the Lyons mine in particular, under temperature conditions which would prevail in a disposal operation. Further, in the Lyons mine, and in practically all existing bedded salt mines, there is considerable water-bearing shale in the floor. All available corrosion data indicate

that stainless steel waste containers will corrode rapidly in the presence of salt and water, possibly to failure in a matter of a few months. It is also reasonably certain, on the basis of existing experimental data, that water from the shale will migrate to the surface of the floor,[3] and that in all likelihood this water which has been in contact with the corroded waste cans will contain some radioactivity.

In an actual operation it may be possible to cope with mine instability and water problems, but at this time it is not apparent what measures would have to be taken and, thus, what cost must be assessed for such measures.

If the fuel assembly demonstration were run in the existing floor of the Lyons mine, some information could be obtained on the behavior of such an area if used for a disposal operation. However, to get definitive information would require significant heating of at least one pillar and, in view of the structural instabilities which have already manifested themselves in this mine, the primary objectives of the demonstration could be jeopardized. Some information could be gained, of course, on the migration of shale-borne water, but migration of such water to the floor surface has already been demonstrated in electrical-heater tests in the Hutchinson mine.

Another consideration involved is the choice of the particular mining pattern in the existing mine. The major portion of the mined area, while generally similar to the modified-checkerboard pattern in current use, really fits no repeating pattern; and, thus, it would be difficult to say that one had chosen a representative area in which to run the demonstration.

It was thus concluded that the demonstration should be run in the periphery of the mine with the fuel cans being located in the relatively pure salt strata which was originally mined, thus, minimizing the water problem and also allowing use of the most desirable experimental layout.

7.2 Alternative Layouts in Specially Mined Areas

Since the demonstration array of seven fuel assembly cans is to be operated in the floor where stresses (and thus flow) are minimum, the possibility of introducing stresses in the vicinity of the array using flat

jacks installed in the floor around the array or by jacking between floor and ceiling was considered. It was concluded that this method would not produce data which could be interpreted in terms of conditions which might exist in an actual operation.

An experimental pattern was considered in which a central square pillar would be surrounded by four heated arrays (the radioactive array, the nonradioactive duplicate array, and two simple heater arrays) and four additional square pillars (Plan I). This pattern, which is included in the Appendix, would yield information on both primary (radiation) and secondary (salt flow) objectives but has the disadvantage that salt flows could be of such nature and magnitude as to jeopardize the primary objectives by forcing the premature removal of the fuel assemblies.

A second pattern (Plan II, also described in the Appendix), consisting of a single rib-pillar with the radioactive and duplicate arrays adjacent, was considered. This pattern would minimize the possibility of interference with the changeout of the fuel assemblies, but would not be likely to yield much information on salt flow.

7.3 Layout Selected for the Test

A third plan (Plan III) was finally chosen which incorporates the best features of Plans I and II and eliminates most of their disadvantages (Fig. 6). In this plan, there would be four rooms, two 30 ft wide and two 40 ft wide. All rooms would be 60 ft long. The center pillar would be 20 ft wide and the other two, 30 ft wide.

If the 30-ft rooms and pillars were a repeating pattern, the extraction ratio would be 50%; and if the 40-ft rooms and 20-ft pillars were repeating, the extraction would be 67%. With these extraction ratios at ambient temperature, the end rooms should show negligible salt flow and the center rooms, not enough flow to produce roof falls or noticeable floor heaves.

The radioactive and duplicate arrays would be contained in the end rooms, and the center pillar would be heated by means of 22 heaters to yield the salt flow data. The temperature-rise pattern in the floor at the heater center-plane (9 ft below floor level) after 1 1/2 years' operation (12,800 hr) of the 22 heaters (1546 w per heater) is shown in Fig. 7.

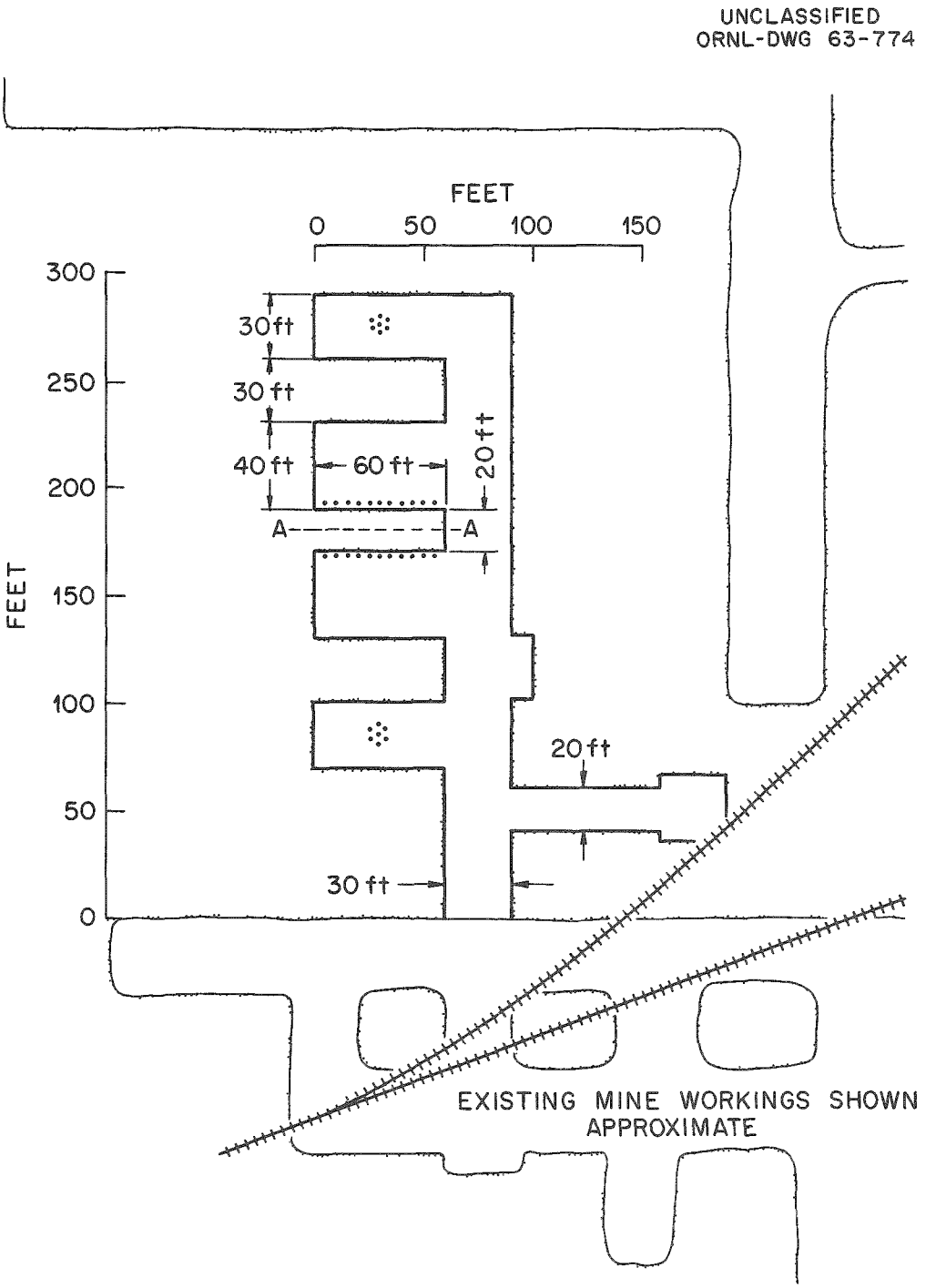

Fig. 6. Proposed Layout for Hot Demonstration Area Room and Pillar Pattern, Plan III.

It may be noted that the major portion of the pillar base will experience temperature rises in excess of 70°C. It may also be noted that the temperature rise in the center of the floor in the end rooms will be negligible, and thus the heating of the center pillars should not have any thermal effect on the radioactive and duplicate arrays. These arrays, however, will contribute to heating of the two 30-ft-wide pillars. (This contribution is not shown in Fig. 7.)

Temperature patterns at other levels and in the vertical planes through the center pillar have not yet been calculated, but a rough idea of what they will look like may be obtained from the corresponding figures for the four-array test (Plan I, Figs. A.7- A.10). The patterns for the radioactive and duplicate arrays will be the same as Figs. A.3-A.6 (Plan II), except that the pillars will be 30 ft wide instead of 50 ft.

The power supply and heaters for the center pillar will be designed so that the heat input may be doubled, thus doubling the center-pillar temperature rises, if desired.

The advantages of this plan over either of the previous plans are: (1) that the area containing the fuel assemblies should be relatively stable even if considerable flow and/or roof falls take place in and around the center pillar (Thus, changeout of the fuel assemblies will not be interfered with.); (2) one pillar can be heated sufficiently to produce significant load transfer and salt flows; (3) the mining pattern is essentially that envisioned for a disposal facility in which space is created specifically for waste storage, and thus the flows and load transfers, and the rates at which they take place, will be valuable empirical information which will be useful in the design of a production facility.

Not shown in Fig. 6 is a third seven-can heater array which will be run in the existing floor of the mine at a location yet to be determined. This array will be started before the main test and will serve as a shakedown test for equipment and procedures, as well as provide comparative data on the effects of the shale beds in the existing mine floor. The fuel assemblies which are removed from the main test array at the end of each 6-month period will be placed in this array so that a dose of the order of 10^8 rad can be delivered to the salt-shale mixture in the floor.

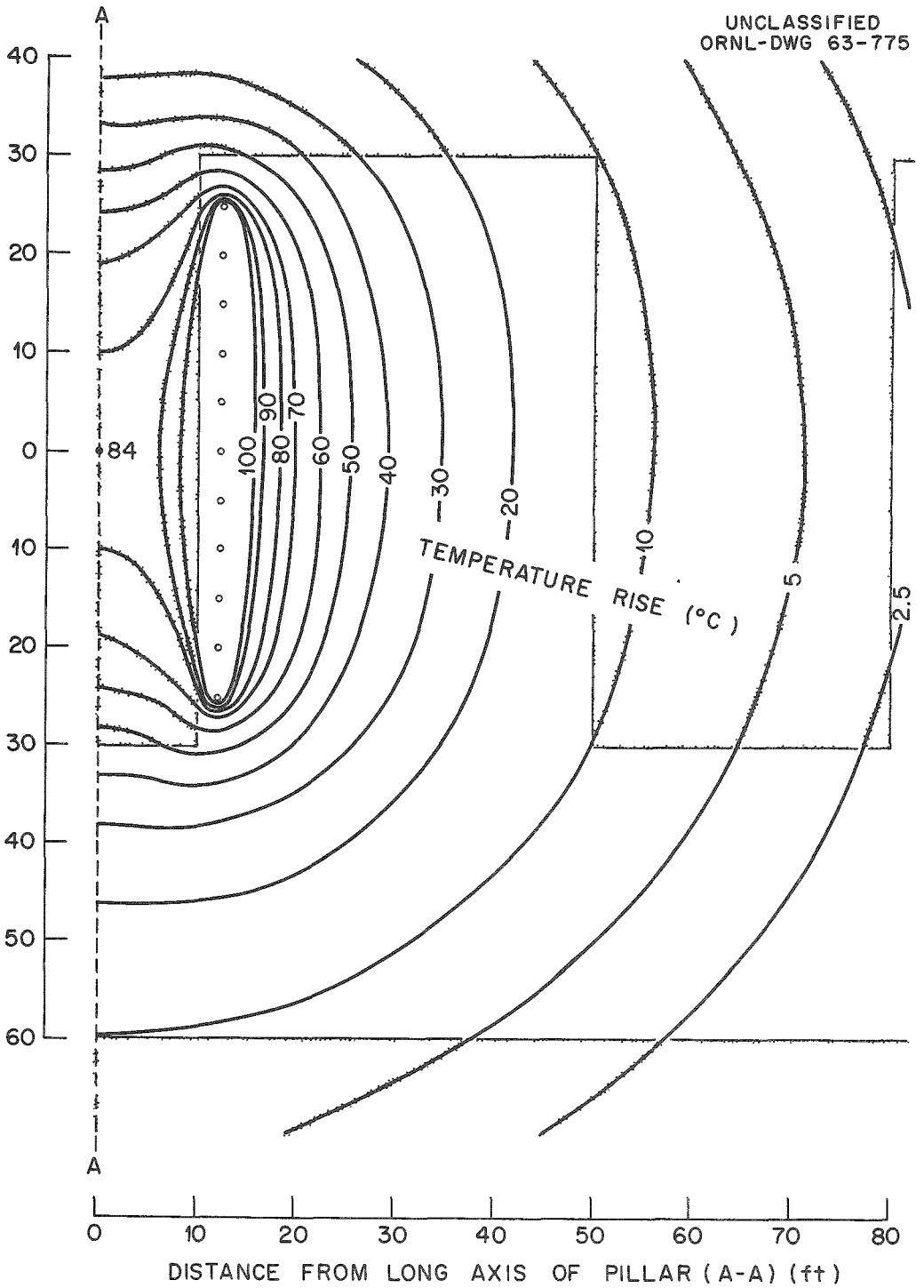

Fig. 7. Nine Feet Below Floor Level; Temperature Rise Isotherms After 12,800 hr Operation of 22 Heaters at Base of Pillar (154o w/heater), Plan III.

8. Experimental Measurements

Details of the instrumentation have not yet been completely worked out, but experimental measurements which are to be made include salt temperatures, salt radiation dose, radiolytic gas production, thermal expansions of floor and pillars, and stress and stress-changes in pillars and other parts of the formation.

It appears desirable to have a total of around 400 thermocouples, based on thirteen thermocouple holes, each containing five thermocouples, located in and around each of the seven-can arrays, plus forty thermocouple holes associated with the center pillar. These forty holes would be located in the center pillar, in the floor around and beneath the pillar, and in the formation at the back of the room.

The method for measuring radiation dose has not been selected, but chemical dosimeters have certain advantages. Several measuring points in the salt will be required.

It is theoretically possible that some radiolytically produced chlorine will be released into the array holes, although laboratory results indicate that the amount will be very small. Thus, it is planned to sample and analyze the gas from the annulus between the salt and the outer can in some of the radioactive array holes. Gas from some of the holes in the duplicate array will also be sampled as a control.

Thermal expansion of the floor in and near the arrays will be measured by means of leveling points related to a bench mark located elsewhere in the mine. Floor-to-ceiling movement can be measured by a portable strain gage. In addition, thermal expansion, along with creep and plastic flow of the pillars, floor, roof, and end walls, will be measured by both surface and internal strain gages. These gages will be installed immediately after excavation so that background creep rates can be obtained. A first approximation of the number of strain gages required is 300 external and 150 internal gages.

Stress meters are currently being investigated, and, if relatively cheap gages prove to be suitable, probably 100 or more will be installed. In any event, some stress determinations will be made before and during the course of the experiment so that the flow data can be more readily interpreted.

The holes in both radioactive and duplicate arrays will have an annulus between the outer can (hole liner) and the salt wall. The annulus will be left free so that comparative measurements of hole closure may be made between the radioactive and duplicate arrays, and salt shattering may be detected, should it occur.

9. Conclusion

This experiment is part of the development program designed to determine the requirements for safe and economical disposal of radioactive wastes in rock salt formations. The salt flow data obtained in this experiment, when combined with the results of theoretical and model studies (yet to be made) on the structural stability of rock salt at elevated temperature and pressure, should allow the design of an actual disposal facility for optimum use of salt space to proceed.

10. References

[1]F. N. Case, Isotopes Division, personal communication, May 16, 1963.

[2]E. D. Arnold and B. F. Maskewitz, SDC: A Shielding Design Code for Fuel Handling Facilities, ORNL-TM-124 (Jan. 25, 1962).

[3]F. L. Parker and R. E. Blanco, Waste Treatment and Disposal Progress Report for November-December 1962, and January 1963, ORNL-TM-516, p 96 (June 12, 1963).

Appendix

Considerations Involved in the Choice of the Experimental Design of the Hot Demonstration

The following is based on Plan A of W. J. Boegly, Jr., and W. F. Schaffer, Jr., which involves creating new space at the mine periphery; however, temperature patterns and general considerations would be much the same if the test were located in the existing floor.

Design of Test Area Layout

Assume that a square pillar is to be heated from one side by the hot array, from the opposite side by the mockup array, and on the other sides by electrical heaters. In order to achieve the maximum temperature rise in the pillar, the smallest pillar possible should be used.

From conversations with Equipment Manufacturers' representatives, it would appear that the waste transporter will be able to turn around in a tunnel 25 ft wide. Thus assume that a 25-ft corridor will be needed around the four sides of the pillar. It would appear to be desirable to maintain a pillar width-to-height ratio of at least 2. Room height will be about 12 ft, and, thus, the pillar should be at least 24 ft square. However, a pillar of this size surrounded by a 25-ft corridor would correspond to greater than 75% extraction if the pattern were repeating. In the older areas of the Lyons mine the extraction was about 75% and floor heaves and roof falls resulted. Even though the experimental area will be small, it would appear desirable to stay below 75% extraction. In the newer areas of the mine (ca. 1940) the extraction was about 65%, and only small floor heaves (not generally visible but evident upon drilling into the floor) have occurred.

The proposed layout for the demonstration area (Plan I) is shown on the attached sketch (Fig. A.1). The pillars are 30 ft square; the corridors around the central pillar are 25 ft wide; and corridors around the peripheral pillars are 17 1/2 ft wide. This would give 70% extraction if the center pillar pattern were repeating, 60% extraction if the peripheral pillar pattern were repeating, and 65% extraction if the

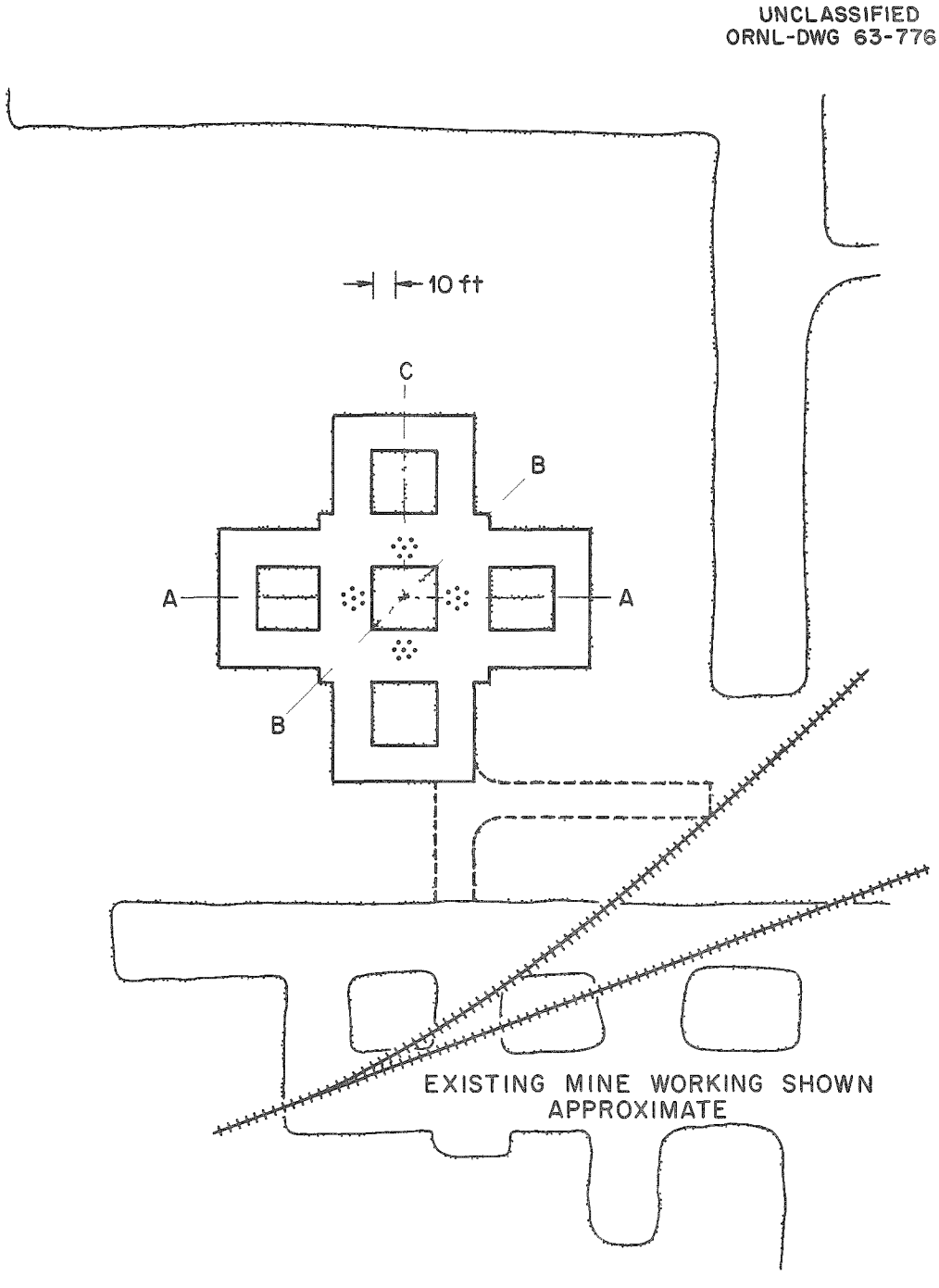

Fig. A.1. Proposed Layout for Hot Demonstration Area, Plan I.

combined five pillar pattern were repeating. If the 175-ft square which completely encloses the experimental area is considered, the extraction is only 46 1/2%.

It seems likely that the surrounding formation will take up part of the load produced by mining the proposed area so that the load on the central pillar will not be as large as would be the case with a repeating pattern. However, at this time there would appear to be no information available on load transfer in an area such as this, and thus the possibility cannot be completely ruled out that considerable flow will take place in the central pillar, even without the addition of heat.

It further appears probable that there will be shale bands in the pillar and in the roof. Shale bands in the pillar will probably result in the "friction reduced" conditions, but how this will compare with the "friction reduced" condition in the floor and ceiling of the existing mine is not known. The presence of shale bands in the ceiling coupled with considerable flow could produce roof falls. If, in the course of the test, it became apparent that ceiling sags were occurring, roof bolting could perhaps eliminate the hazard or the ceiling could be knocked down. Such action might not be desirable during the operation of the hot test.

From the standpoint of gaining the most information on plastic flow and load transfer, it would actually be desirable to produce complete failure of the pillar by heating. Since the possibility exists that this could jeopardize the hot demonstration, it might be better to mine only one rib pillar instead of five square pillars. A possible layout (Plan II) is shown in the attached sketch (Fig. A.2) for the proposed layout using minimum mine space. In this layout, rooms and corridors are 30 ft wide and minimum pillar thickness is 35 ft, corresponding to 46% extraction. In the area containing the hot and mockup arrays, the pillar width is 50 ft, corresponding to 37 1/2% extraction.

As will be shown later, the two arrays will not interact thermally with each other during a 2-year period of operation, though both will contribute to the heating of the rib pillar. Peak temperature rises under the edges of the pillar will be about 30°C, and under the center

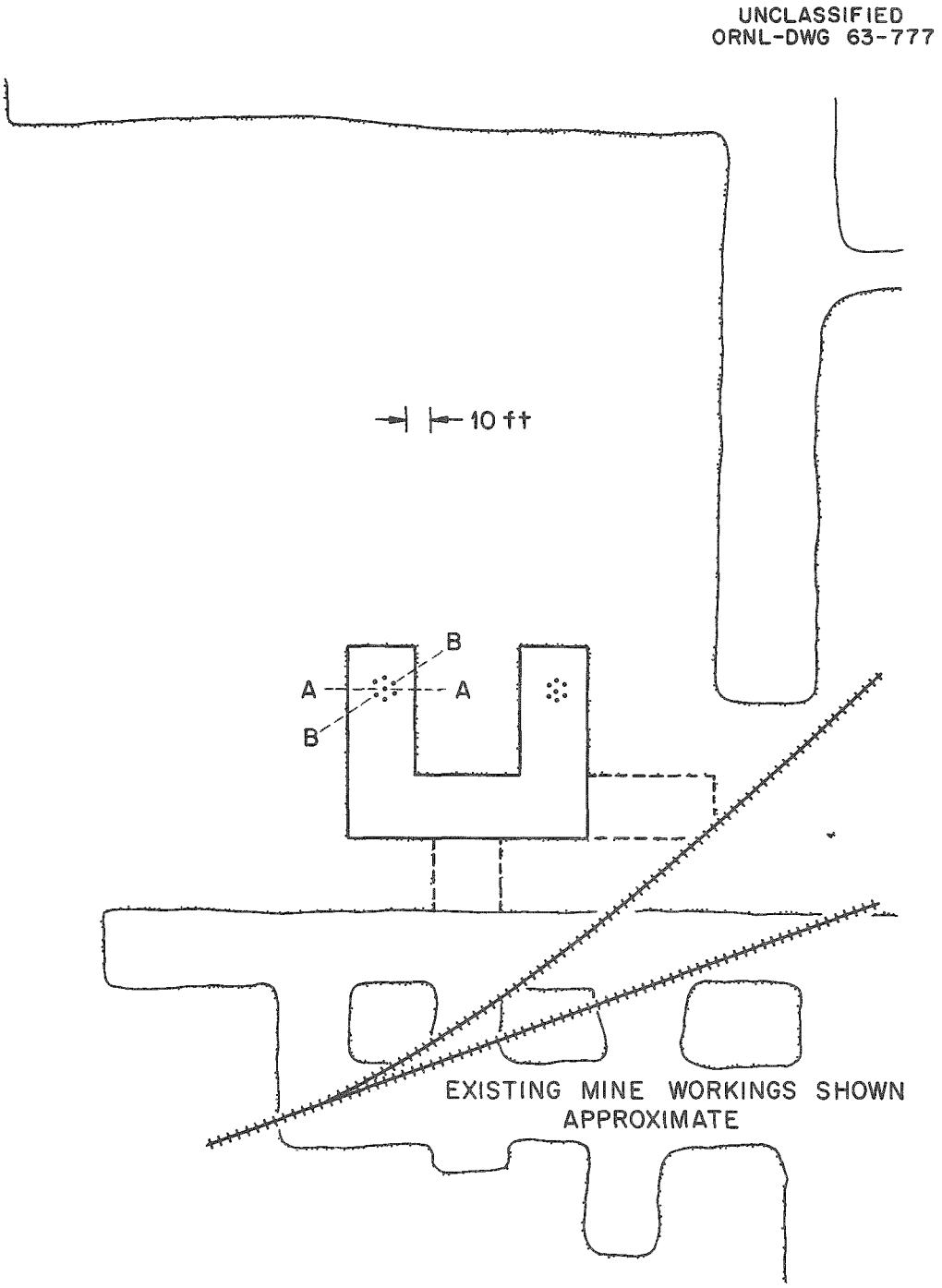

Fig. A.2. Proposed Layout for Hot Demonstration Area Using Minimum Mine Space, Plan II.

of the pillar about 20°C. This is in contrast to the five-pillar plan where temperature rises under the central pillar may be in excess of 70°C. Thus the single rib pillar plan is much more conservative than the five-pillar plan, both in pillar loads and in pillar temperatures. Since creep and plastic flow increase rapidly with increasing pressures and temperatures, in the rib pillar plan there would be much less chance of operational difficulties caused by excessive salt flow.

Studies of Salt Temperature Patterns to be Expected In Hot Demonstration

Based on an examination of the apparent thermal properties of salt as determined from the liquid cavity and cylindrical heater tests, it appears that theoretical calculations based on the 100°C properties should be sufficiently accurate for use in the design of the experiment. In regions where the temperature is of the order of 200°C, the theoretical predictions may be expected to be around 10% low; and, for regions of temperatures well below 100°C, the predictions may be high.

A peak salt temperature of 200°C has been used as the limiting temperature in the study of the economics of salt disposal. This value is well below the point at which shattering of the salt has been found to take place (above 250°C). Since the amount of salt which must be mined is a direct function of the peak allowable temperature, 200°C would appear to be a logical peak salt temperature to aim for in the hot demonstration.

Calculations were made assuming an array of seven heat sources, 6 ft long, arranged in a hexagonal array with 5 ft on centers spacing of the sources. Thermal conductivity and diffusivity of salt at 100°C, as determined by Birch, were used. Constant heat-generation rate was assumed, and it was found that the salt temperature rise at the periphery of the center heater hole will be within 95% of the steady-state value after 1 1/2 years (12,800 hr).

In order to achieve 180°C rise after 1 1/2 years' operation of the heaters, it was found that the heat-generation rate should be 1546 w per heater. In Fig. A.3 are shown the temperature rise curves for the

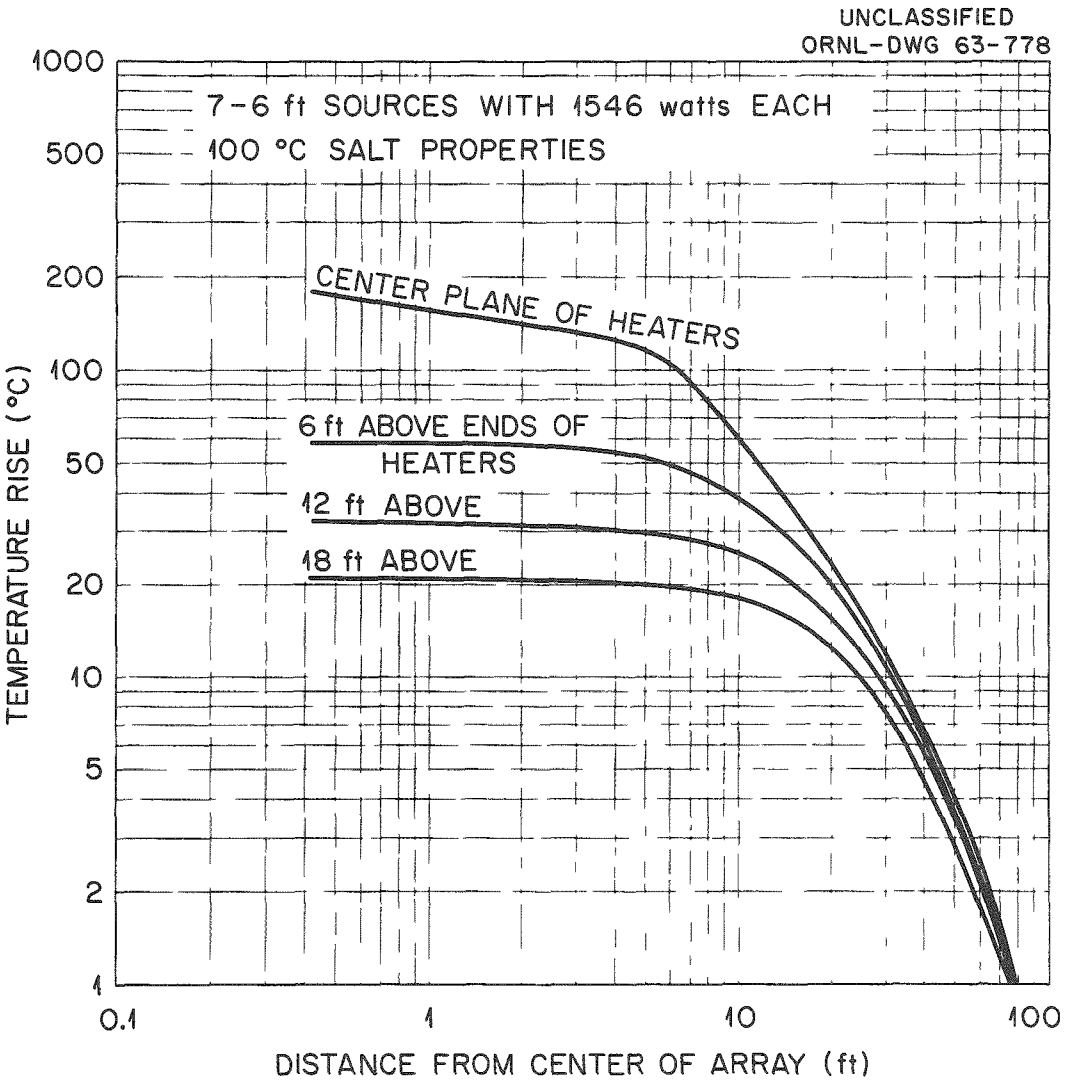

Fig. A.3. Temperature Rise Profile in Demonstration Array Along Radial Between Peripheral Heaters After 12,000 hr.

horizontal planes at the center of the heaters and 6, 12, and 18 ft from the ends of the heaters. The curves are for radials running out between two peripheral heaters and, thus, correspond to minimum temperature curves. A radial running through the center of a peripheral heater would show a discontinuity at 5 ft from the center of the array and would be somewhat higher in temperature from about 3 ft on out to 10 or 15 ft.

Vertical cross section A-A from Fig. A.2 (rib pillar Plan II) is shown in Fig. A.4, along with the temperature contours for the seven-can array after 1 1/2 years' operation. No allowance was made for the fact that salt has been removed to create the room. Thus the temperature rises shown in the pillars are expected to be high. Also, there will be more heat lost through the floor to the air than would flow vertically if the room were not there, and the contours will tend to neck in toward the center of the array. This effect can be minimized by insulating the floor of the room. Insulation of the pillar would also help to raise its temperature.

Figure A.5 shows a plan view of the rib pillar pattern (Plan II) with temperature contours at a depth of 9 ft below the floor (midplane of the array). The contribution from the mockup array is not shown, but it would be approximately a mirror image radiating from the center of the right-hand room. The isotherms are shown as circles in this figure, but there would actually be some ripples on the contours as they pass peripheral heaters.

Figure A.6 shows isotherms at floor level for the same conditions as Fig. A.5.

The five-pillar pattern cross section A-A (Fig. A.1, Plan I) is shown in Fig. A.7, along with the temperature contours produced by four arrays running simultaneously. The peak rise adjacent to the center heater hole is about 200°C after 1 1/2 years' operation. If the mockup array and one of the other arrays were started, say, 6 months earlier, the peak temperature rise might be a little more than 200°C. This might be satisfactory, or, if desired, the center heater power could be reduced to limit the rise to 180°C.

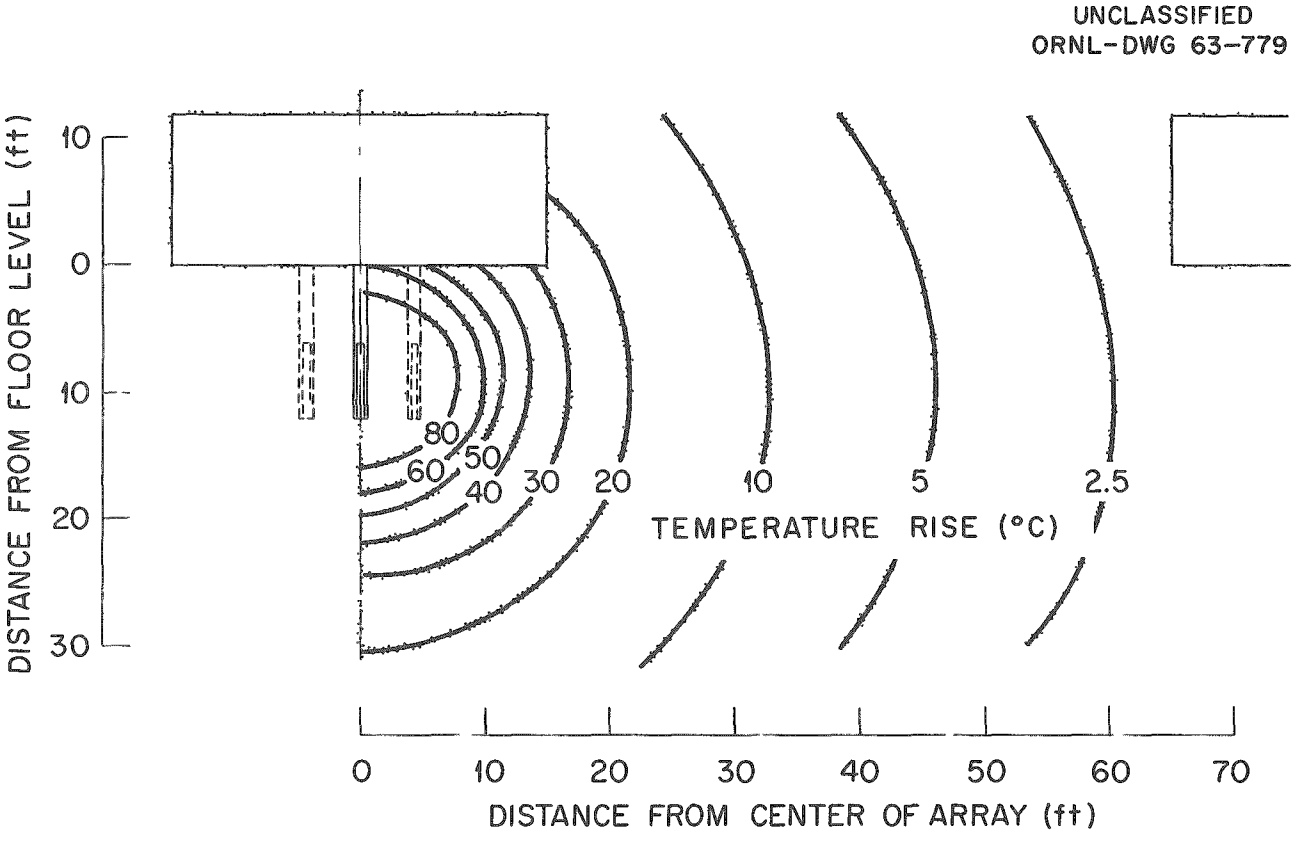

Fig. A.4. Temperature Rise Isotherms After 12,800 hr Operation of One Array (7 cans, 1546 w/can, 100°C Thermal Properties of Salt). Vertical Cross Section A-A, Plan II.

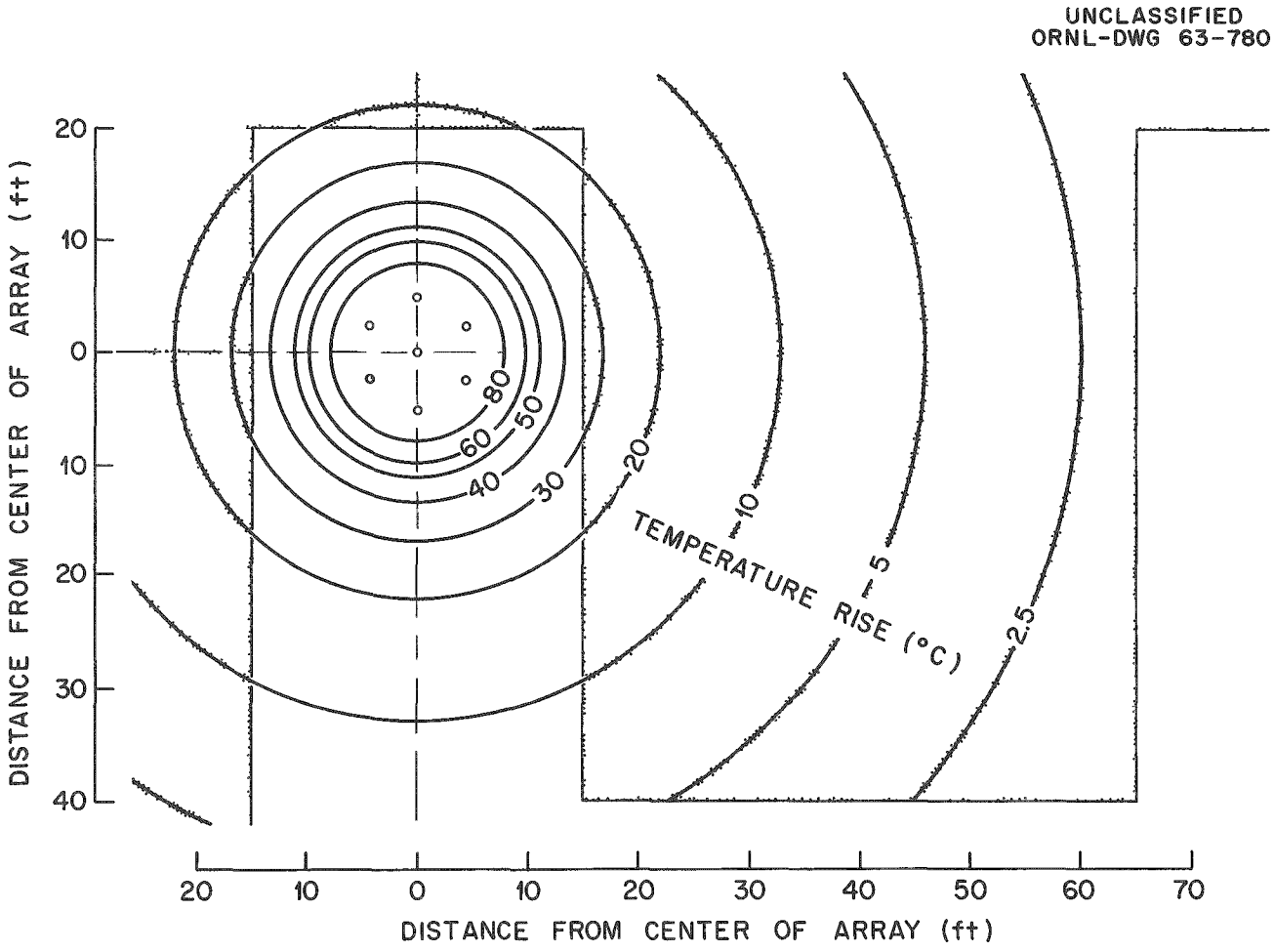

Fig. A.5. Nine Feet Below Floor Level-Temperature Rise Isotherms After 12,800 hr Operation of One Array (7 cans, 1546 w/can, 100°C Thermal Properties of Salt), Plan II.

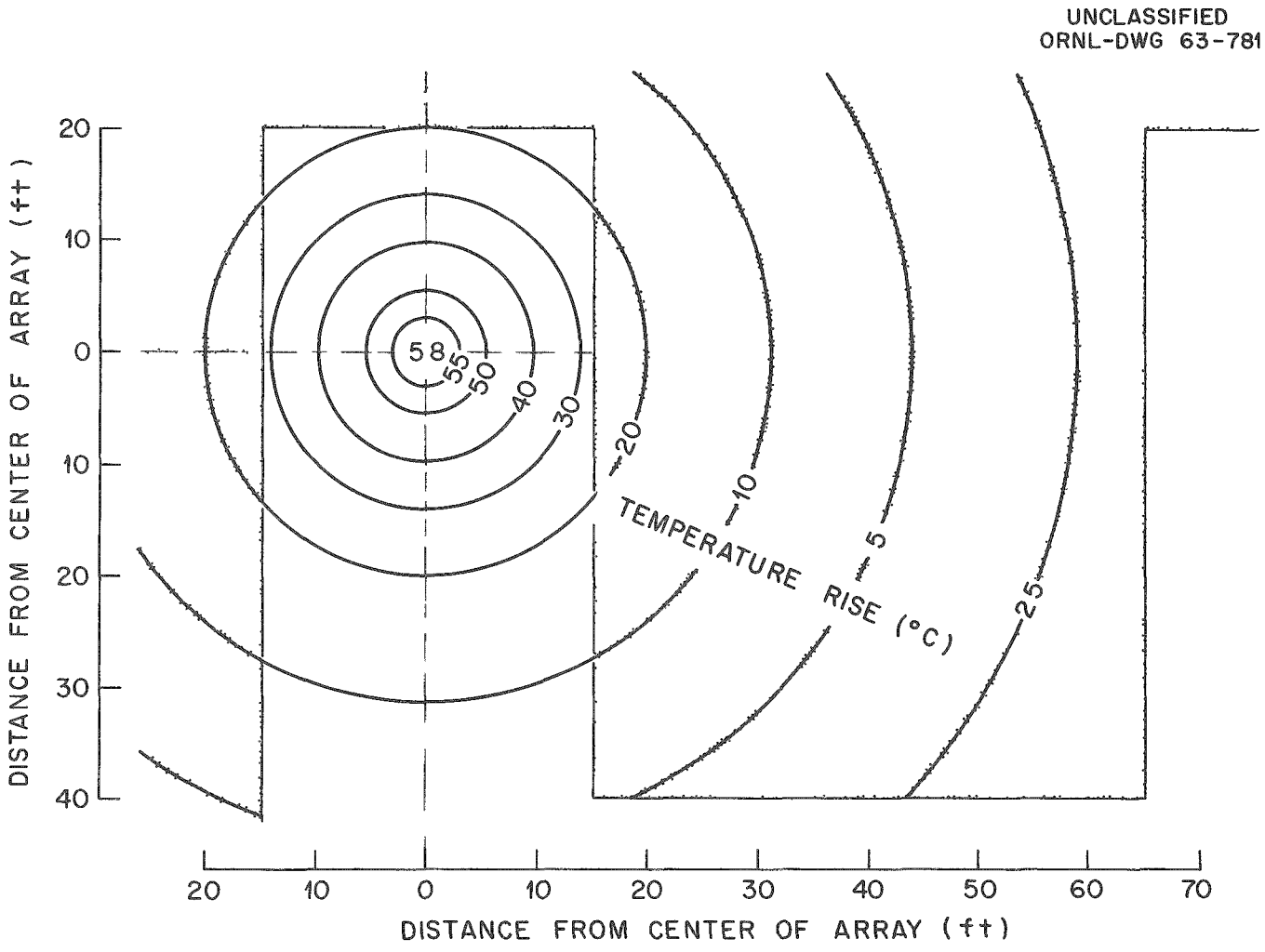

Fig. A.6. Floor Level Temperature Rise Isotherms After 12,800 hr Operation of One Array (7 cans, 1546 w/can, 100°C Thermal Properties of Salt), Plan II.

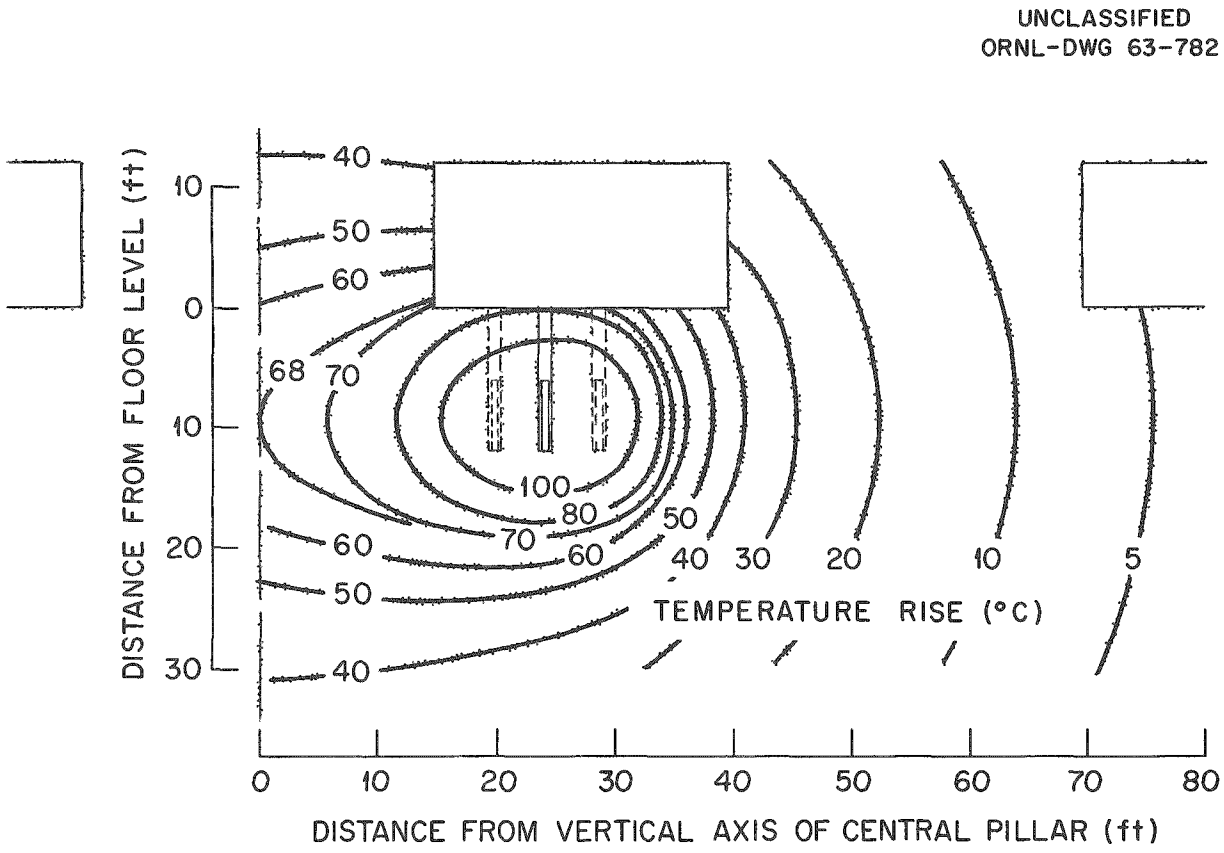

Fig. A.7. Temperature Rise Isotherms After 12,800 hr Operation of Four Arrays Around Central Pillar (7 cans per array, 1546 w/can, 100°C Thermal Properties of Salt), Plan I.

Cross section B-B, along the pillar diagonal, is shown in Fig. A.8. In all these figures the effects of the presence of the room on the temperature patterns has been neglected as mentioned previously.

Figures A.9 and A.10 show the isotherms in the horizontal planes of quadrant C-A at 9 ft below the floor and at floor level, respectively. From figures A.7 through A.10, it may be seen that essentially the entire area beneath the central pillar down to a depth of 18 ft will have rises in the range of 60 to 70°C. The entire pillar is seen to rise about 40°C at the top and 60°C at the bottom. With insulation of the pillar and of the floor, it seems likely that a large fraction of this rise can actually be achieved.

It may also be seen that appreciable temperature rises will be produced in and beneath the peripheral pillars (20 to 30°C over large portions of the pillars) and as much as 5 to 10°C in parts of the surrounding formations.

Analysis of Objectives and Relative Merits of Five-Pillar Plan And Single Rib Pillar Plan

In the rib pillar plan (Plan II) the objectives would be: (1) to demonstrate the handling of the fuel assemblies; (2) heat up a fairly large mass of salt to above 100°C while achieving a peak salt temperature of 200°C at the center of the array; (3) determine if any gross effects are produced by combined heat and radiation (These effects would be measured by comparison with the mockup; that is, faster salt flow rates, greater closure of holes, or shattering of salt around the fuel elements.); (4) determine if chlorine or any other hazardous chemicals are radiolytically produced in detectable quantities; (5) design the test and operate it in a manner such that the expected flow of salt will not complicate the operation in any significant way; (6) obtain such creep, plastic flow, and overburden load transfer information as may be possible (With only a few degrees rise in the pillar, it is not believed that much flow will take place, and this flow will likely be masked by thermal expansion. If flow is small, overburden load transfer should also be small, and it may or may not be measurable with existing techniques.).

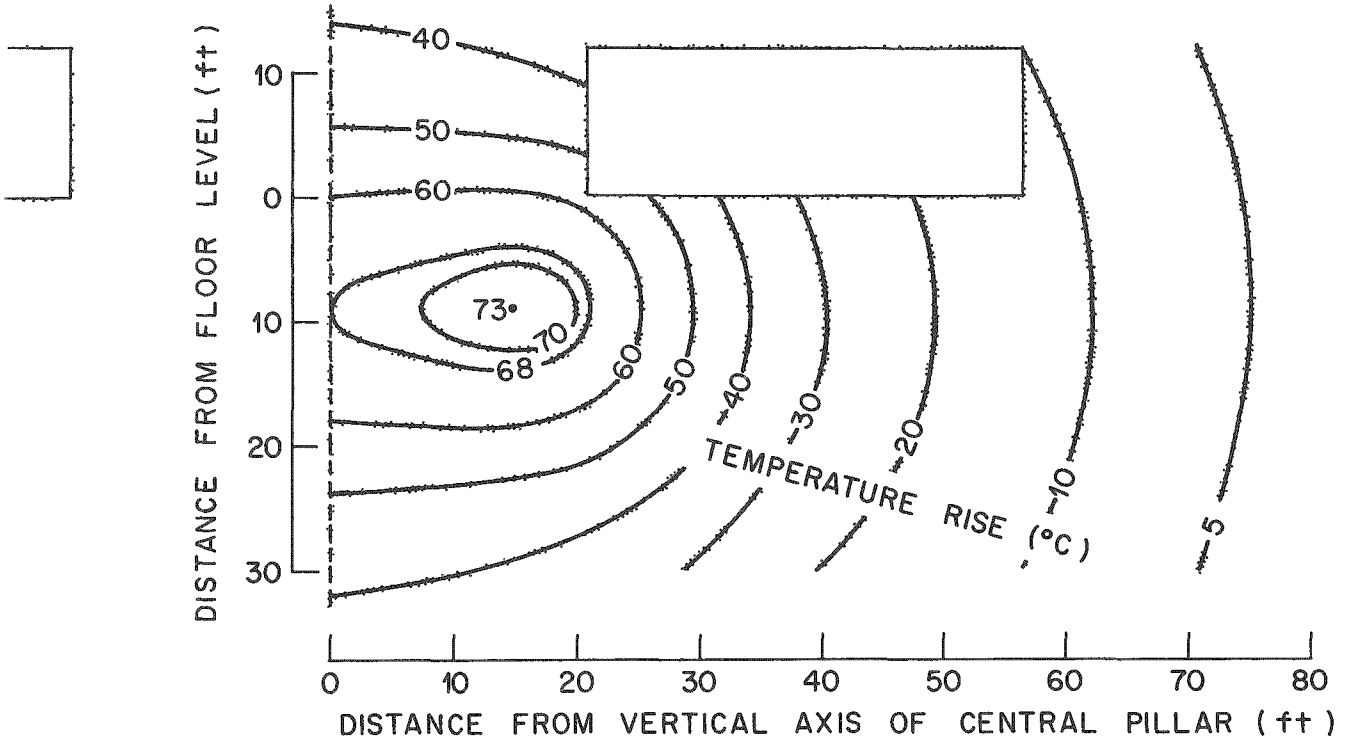

Fig. A.8. Temperature Rise Isotherms After 12,800 hr Operation of Four Arrays Around Central Pillar (7 cans per array, 1546 w/can 100°C Thermal Properties of Salt). Vertical Cross Section B-B, Plan I.

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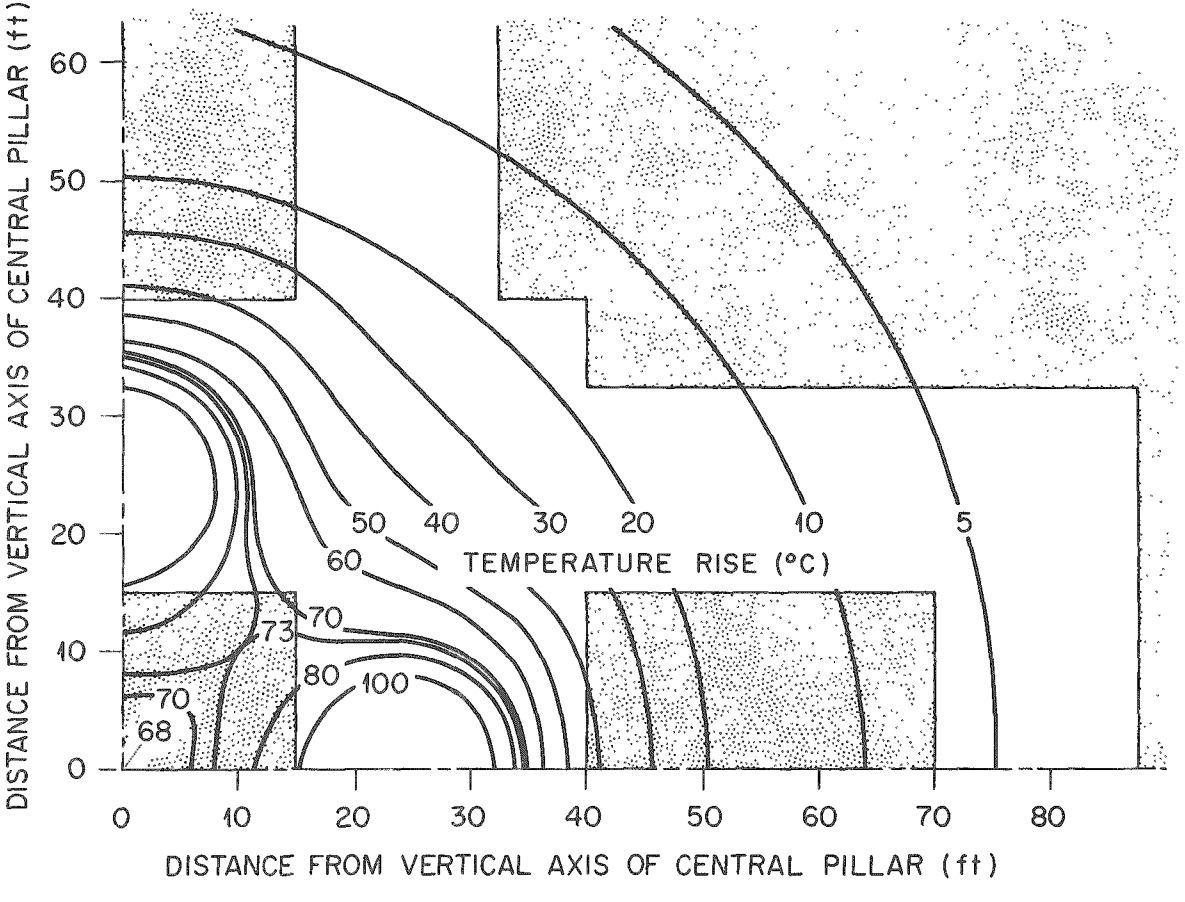

Fig. A.9. Nine Feet Below Floor Level, Quadrant C-A; Temperature Rise Isotherms After 12,800 hr Operation of Four Arrays Around Central Pillar (7 cans per array, 1546 w/can, 100°C Thermal Properties of Salt), Plan I.

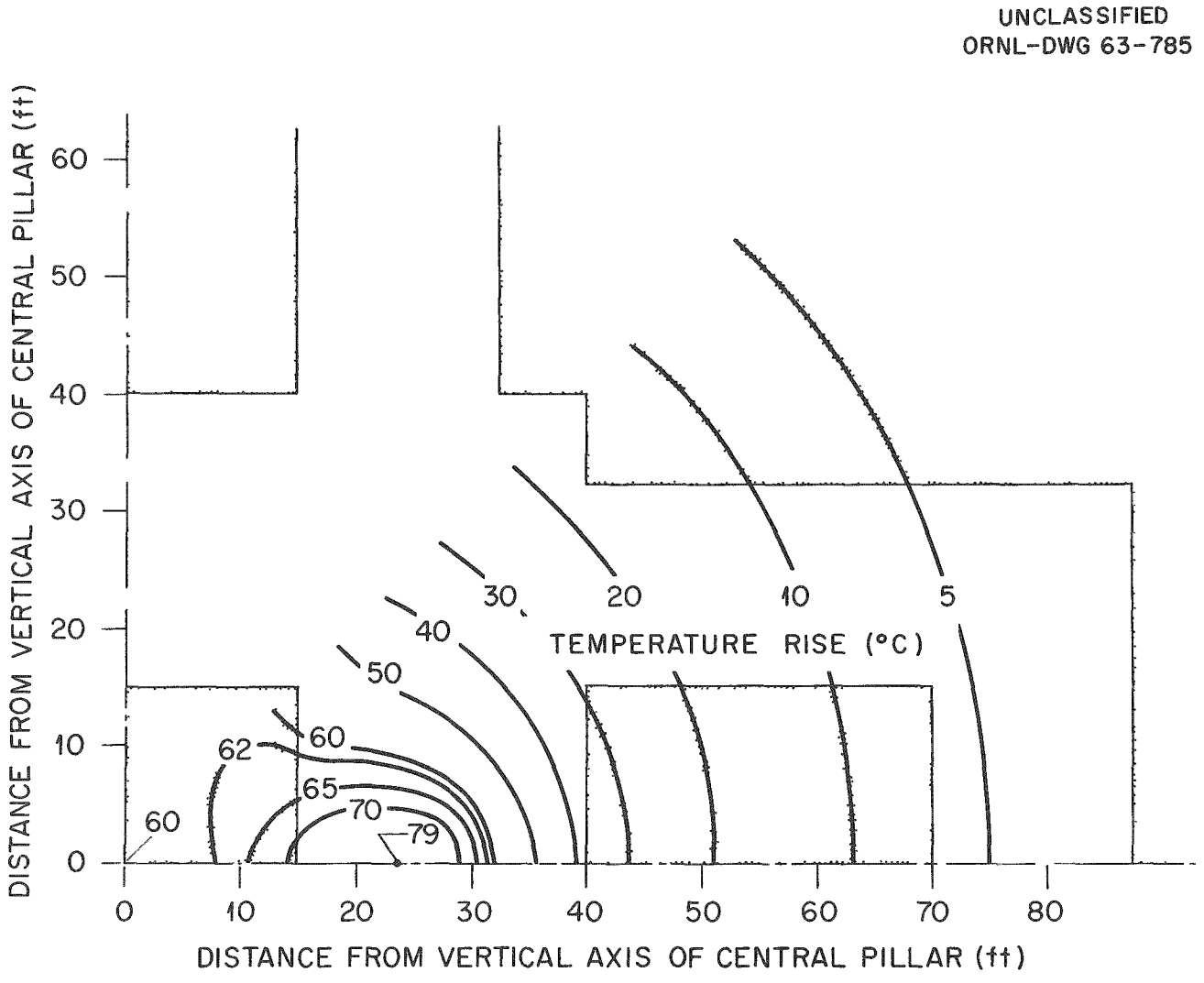

Fig. A.10. Floor Level Temperature Rise Isotherms, Quadrant C-A, Plan I.

In the five-pillar plan (Plan I), the first four objectives are the same as for the rib-pillar plan. (However, item 3, synergistic effects, might be compromised slightly if the mockup and hot array were not started simultaneously, since there will be thermal interaction between the two.)

The fifth objective is now reversed. Instead of designing for minimum salt flow, the five-pillar plan calls for maximum heat in the pillar coupled with higher pillar pressures to produce a significant flow and consequent transfer of overburden load.

The sixth objective, to obtain the maximum of information on creep, plastic flow, and overburden load transfer, should be augmented by the fifth objective. However, it is not certain that it will be possible to interpret the flow data, even though much greater flow occurs. Since the peripheral pillars will be heated appreciably, and even a portion of the surrounding formation may see a few degrees rise, it may prove difficult to differentiate thermal expansion from increased creep or plastic flow. Depending on the rate and manner in which load transfer takes place, it may or may not be possible to determine load transfer directly from stress measurements.

In the final analysis, the five-pillar plan will come much nearer to duplicating conditions which would be encountered in an actual disposal operation. The area beneath, around, and in one pillar will be raised to temperatures which are of the same order as those in an actual operation, whereas the rib-pillar test will only raise an area in the center of the room to temperatures approaching operation. On the other hand, the five-pillar plan is much more likely to produce flows or roof instabilities which, while not necessarily undesirable and perhaps even desirable in an operation, could cause difficulties in the loading and unloading of fuel assembly cans in the array.

Neither test will yield all the information which will be needed to establish design criteria for a disposal operation; however, if unforeseen behavior or problems were to exist, they might become apparent in the rib-pillar test but would be much more likely to be evident in the five-pillar test.

In order to develop production facility design criteria, it will be necessary to do model and/or theoretical studies; and, to develop confidence in the results, it will be necessary to check at least one point in a full-scale test. Either of these proposed demonstration tests could be used as the check point, but, again, the five-pillar plan would seem to be more suitable for the purpose. However, it might very well be that a different test would be desirable for check purposes, since it could prove difficult to duplicate either of these tests theoretically or in a reasonably scaled model.

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