Cost evaluation of radiation-cured concrete-polymer materials for pipe manufacture

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Chemistry & Accelerator
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Concrete Research Laboratory
Karlstrup
Aktieselskabet Aalborg
Portland-Cement-Fabrik

BFL-IR-236

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by

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Abstract

A conceptual design and preliminary cost evaluation was made for the production of radiation-cured plastic impregnated concrete pipes with internal diameters of 30 and 150 cm respectively and a length of 200 cm.

The calculation of the Co-60 source strength was based on linear absorption of radiation from an infinite rod source using data for mass stopping power and build-up factors as for shielding calculations.

The evaluation was only based upon obtainable increase in strength properties, whereas improvement of corrosion resistance was not especially considered.

Production costs for plastic impregnated concrete pipes with strength properties of the same order as those of steel-reinforced pipes or pipes otherwise "refined" were about 50% higher than for these pipes.

With a growing market need for corrosion-resistant pipes, e.g. for sewage and industrial waste water, it cannot be excluded that even considering the rather high production costs, [illegible] use of plastic-impregnated concrete pipes [illegible] of interest also from an economic [illegible] [illegible] to [illegible]

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Contents

Cost Evaluation of Radiation-Cured Concrete-Polymer Materials for Pipe Manufacture[x)]

by

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1. Introduction

Experimental work on radiation-cured concrete-polymer materials has been started as a joint programme by the Concrete Research Laboratory, Karlstrup, and the Danish Atomic Energy Commission, Research Establishment Risö.

Preliminary investigations included a number of material combinations: light-weight concrete, normal-strength concrete and high-strength vibropressed concrete, various hard-compressed cement-sand mortars, sand-lime bricks and plaster of Paris impregnated with methylmethacrylate, styrene/acrylonitrile and unsaturated polyesters. Large increases in compressive strength and splitting tensile strength were obtained. Thus compressive strengths of more than 2000 kg/cm^2 were reached with a special concrete.

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x) Presented at the Conference on Radiation and Isotope Techniques in Civil Engineering, Brussels, October 28-29, 1970.

As a guide to the future research programme it was decided to make a conceptual design and preliminary evaluation study in direct collaboration with Danish Manufacturers of concrete pipes and concrete pipe machines. The purpose of these investigations was to evaluate the possible advantages of introducing plastic impregnation in concrete pipe production.

The polymer impregnation process was considered to be of greatest interest for unreinforced pipes of large dimensions. It was therefore decided to calculate and optimize the production plant for one dimension: a circular pipe with an internal diameter of 160 cm and a length of 200 cm was chosen. The conceptual design for the entire plant was made for this dimension, and the thickness of the concrete pipe was chosen so that maximum efficiency of the radiation source was obtained. This was done in order to find the most promising design for the process.

It is assumed that the final plant could also be used for production of pipes of somewhat smaller dimensions. It was, however, also of interest to make an evaluation of a plant for much smaller pipes with, for instance, an internal diameter of 30 cm and a length of 200 cm. For this evaluation the plant described by Kukacka, Steinberg and Manowitz (ref. 1) was considered suitable.

2. Plant Description for Large Pipes

2.1. Design Premises

It was found that the concrete in this type of pipes could be impregnated with four weight per cent of polymethyl methacrylate. Experimental results showed that a tensile strength in bending of two hundred kg/cm^2 could be expected, and this value was used for determination of the relation between wall thickness and supporting strength of the pipes. As a result of an optimization calculation for the design of the radiation source a wall thickness of 12 cm was chosen. A pipe with this thickness and a total weight of 3,250 kg has the same supporting strength as an unimpregnated and unreinforced pipe with a wall thickness of 20 cm and a weight of 5,600 kg.

2.2. Plant Lay-out

A conceptual design for a facility to produce twenty-four large pipes per day of plastic-impregnated concrete is shown in figure 1. The plant consists of a drying oven, an impregnation tank and twenty-four separate irradiation holes. Furthermore the plant comprises a monomer storage tank, pumps, transporting systems, and a dip tank.

A typical process cycle would be as follows: each concrete pipe is placed on a separate carrier and wheeled into the drying oven which can contain twenty-four pipes at the same time. Eight pipes are taken out for cooling after twenty-four hours of drying and are then taken to the vacuum- and impregnation tank. The tank is sealed and evacuated. After a prescribed period of evacuation the tank is charged with monomer from the monomer storage tank, and the pipes are then impregnated so that the total evacuation - impregnation cycle takes eight hours. The monomer is pumped back to the storage tank, and the pipes are taken out one by one, lifted up by a double-rail, overhead travelling crane and dipped in the dip tank containing a viscous solution of polymer in monomer in order to minimize evaporation losses. Finally the pipe is placed on a tray which will take up excess monomer and then in an empty irradiation hole. A concrete shielding plug is then placed over the irradiation hole and the source is raised into irradiation position from the shielded [illegible] below the irradiation hole and is kept there for twenty-four hours of irradiation.

For calculation of the total [illegible] necessary, and hence the source strength, it is [illegible] are necessary to estimate the [illegible]

2.3. Design of Radiation Source

2.3.1. Radiation Dose

On the basis of experimental work it was concluded that the minimum radiation dose required for complete polymerization of methyl methacrylate, impregnated into concrete, would be 2.0×10^6 rads at a dose rate of 3.5×10^5 rads/hour. The calculations are furthermore based on the assumption that the minimum curing dose, D_{min}, varies proportionally to the square root of the dose rate, R, i.e.

$$D_{min} = K \sqrt{R}.$$

On the basis of this equation and on the experimental set of values for D_{min} and R, and furthermore on the fact that D = R x T (where T is the irradiation time) it is possible to calculate R and D_{min} for a given T.

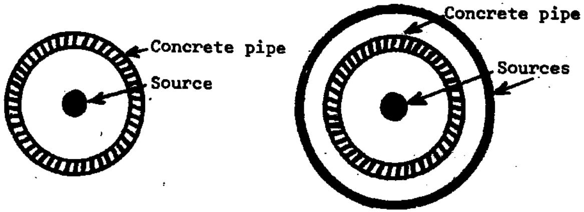
For an irradiation time of twenty-four hours we find: $D_{min} = 4.75 \times 10^5$ rads, and $R = 1.98 \times 10^4$ rads/hour.

2.3.2. Irradiation Geometry

The absorbed radiation dose decreases with increasing concrete thickness. Figure 2 illustrates the relative absorbed dose as a function of concrete thickness for normal concrete, $\rho = 2.40$ g/cm^3. Data for mass stopping power and build-up factor are given in references 2 and 3.

Among the different geometries taken into consideration the single-rod source in the centre of the concrete pipe was found to be the most economic((a) on next page).

A geometry for two-side irradiation (b) requires 20% greater source strength and more complicated source handling equipment. Any geometry including moving sources or moving target gives higher "local" dose rates, and thereby lower utilization of the source.



(a) (b)

2.3.3. Source Strength

The basic calculation criterion is that the outer side of the concrete pipe should receive the required minimum radiation dose during the prescribed irradiation time. As the absorbed dose will increase directly proportionally to the dose rate as the distance to the central source decreases right through the pipe wall (D = T x R), whereas the required minimum dose for polymerization will increase only proportionally to the square root of the dose rate ($D_{min} = K\sqrt{R}$), all other parts of the concrete pipe will absorb more than the required minimum dose, ensuring complete curing of the impregnated monomer.

From the curve in figure 2 it is possible to calculate

- the average radiation dose absorbed in the concrete pipe when the required minimum dose for the outer part of the pipe is known, and
- the fraction of transmitted, i.e. lost radiation energy.

For calculation of the total [illegible] necessary and [illegible] more necessary to [illegible] at the ends of the pipe and the losses due to selfabsorption in the source.

For an irradiation time of twenty-four hours we find:

Dmin		4.75×10^5 rads
R		1.98×10^4 r/hour
Average dose		1.07×10^6 rads
Average dose rate		4.45×10^4 r/hour
Total absorbed energy per hour ..		1.45×10^6 joules/h
Loss due to transmission		0.43×10^6 -
Loss due to selfabsorption	estm.	0.22×10^6 -
Loss at the ends	estm.	0.15×10^6 -
Total radiation energy per hour		2.25×10^6 joules/h

$$\text{Source strength: } 2.25 \times 10^6 \times \frac{1}{51.1} \text{ Ci } {}^{60}\text{Co}$$

$$= 44.000 \text{ Ci } {}^{60}\text{Co.}$$

This is the source strength necessary to irradiate one concrete pipe a day (twenty-four hours).

For the production of twenty-four concrete pipes a day the total source strength will be 1,100,000 curies.

It should be noted that the calculations are based on linear absorption of radiation from an infinite rod source. The estimate of loss at the ends of the pipe might be somewhat optimistic.

2.3.4. Factors Influencing the Design and the Source Strength

2.3.4.1. Irradiation Time

The necessary source strength per pipe will decrease greatly with increasing irradiation time owing to the square root dependence of the dose on dose rate. On the other hand an increase of irradiation time will necessitate a correspondingly larger number of radiation sources in order to maintain the same production capacity.

For reasons of comparison the source strength per pipe, the number of sources and the total source strength required for irradiation of twenty-four large concrete pipes a day are listed below for three different irradiation times:

Irradiation time hours	Source strength per pipe Ci Co-60	Number of Co-60 sources	Total source strength Ci Co-60
8	400,000	8	3,200,000
24	44,000	24	1,100,000
48	11,000	48	530,000

Depending on the costs of Co-60 and unit costs of irradiation facilities as well as on other building costs the abovementioned mutual dependence may strongly influence the final design of a production plant.

2.3.4.2. Wall Thickness of Concrete Pipe

According to the curve in figure 2 the energy losses by transmission and the effective utilization of the absorbed radiation dose will depend on the wall thickness of the concrete pipe.

Rough calculations show that for wall thicknesses of more than approximately twenty cm the average dose absorbed (and hence the source strength) will increase so much that irradiation from two sides must be considered. On the other hand at thicknesses below approximately eight cm the energy transmission will be so great that simultaneous irradiation of more than one wall thickness of concrete pipe should be considered. This is in good agreement with the design of an irradiation facility reported in reference 1, for the irradiation of 3,8 cm (1½ inch) thick concrete pipes. In this design an irradiation through four times the wall thickness, i.e. a total of fifteen cm of [illegible]

3. Plant Description for Small Pipes

3.1. Design Premises

The pipe chosen for this evaluation has the following dimensions: 30 cm i.d. x 200 cm length x 3.8 cm wall thickness. Assuming, as for the large pipes, an impregnation with four weight per cent of methyl methacrylate and a flexural strength of 200 kg/cm^2 of the treated concrete, this pipe with a total weight of 205 kg has the same supporting strength as an unimpregnated and unreinforced pipe with a thickness of 6.7 cm and a weight of 390 kg.

3.2. Plant Lay-out

The conceptual design for a facility producing one hundred and sixty-eight pipes a day with the following dimensions: 30 cm internal diameter, 200 cm length and a wall thickness of 3.8 cm, was chosen in accordance with that described in reference 1. The design in this investigation implies the simultanous irradiation of a number of pipes resulting in irradiation through four times the wall thickness, a total of about fifteen cm of concrete (see figures 3 and 4).

3.3. Radiation Source Strength

In agreement with the principles of calculation outlined in 2.3.3. we find for the irradiation of fifty-six pipes in eight hours (168 pipes a day) with a source geometry as described in ref. 2:

Dmin	1.4×10^6 rads
R	1.75×10^6 rads/hour
Average dose	4.2×10^6 rads
Average dose rate	5.25×10^5 rads/hour
Total absorbed energy per hour	4.94×10^7 joules/hour
Loss due to transmission, estm.	1.48×10^7 "
Loss due to self-absorption, estm. ..	0.74×10^7 "

Loss at the ends, estm.	0.50×10^7 joules/hour
Total radiation energy per hour	7.66×10^7 joules/hour

$$\text{Source strength: } 7.66 \times 10^7 \times \frac{1}{51.1} \text{ Ci } {}^{60}\text{Co}$$

$$= 1.5 \times 10^6 \text{ Ci } {}^{60}\text{Co.}$$

4. Initial Investments

4.1. Plant for Large Pipes

The plant costs have been estimated on the basis of separate cost evaluations for the different pieces of equipment necessary for the manufacture: drying oven, evacuation/impregnation tank, dip tank, monomer storage tank, twenty-four irradiation holes, pumps, transporting systems, and building costs. The total facility costs for this plant, which do not include the Co-60 costs and the source moving mechanism, are estimated to be as follows:

Irradiation holes		kr.[x)] 240,000
Buildings (1250 m^2 high building + 800 m^2 low building)		" 1,500,000
Drying oven		" 500,000
Evacuation/impregnation tank		" 400,000
Monomer tank and pumps etc.		" 240,000
Transporting systems:		
Crane	kr. 165,000	
Trolleys	" 70,000	
48 wheeled carriers	" 415,000	
Rails etc.	" 70,000	" 720,000
Facility cost		kr. [illegible]

[illegible]

4.2. Plant for Small Pipes

In their study Kukacka et al. (ref. 1) have estimated the facility costs for a plant with a throughput of approximately 580 pieces/day, in four-hour shifts - corresponding to approx. 98 pipes per cycle - with a length of 3 ft (approx. 100 cm) to be in the range of \$400,000 and \$460,000 for radiation source strengths of 3.75 and 4.65 x 10^5Ci Co-60 respectively. Their evaluation is based on the assumption of a radiation dose for total cure of 0.5 Mrad.

The present study involves a considerably higher radiation dose for total polymerization of the impregnated monomer and hence a larger radiation source, which demands more shielding. The prescribed production capacity of 168 pipes per day, in eight-hour shifts, and with a length of 200 cm, corresponding to 56 pipes per cycle, requires a plant of approximately the same dimensions as the one described in the abovementioned report. For this plant the costs have been estimated to be as follows based on local conditions:

Earth shielding and concrete doors		kr. 50,000
Buildings (covering the drying oven and trolley rails)		" 500,000
Drying oven		" 300,000
Two impregnation/irradiation tanks		" 500,000
Transporting systems:		
Wheeled carriers	kr. 280,000	
Two trolleys	" 70,000	
Rails etc.	" 80,000	" 430,000
Monomer tank + pumps		" 200,000
Facility cost		kr.1,980,000

4.3. Cobalt-60 Sources

For Co-60 two cost estimates are made that are considered to be the lower and upper limits for encapsulated sources in megacurie quantities: 2.00 and 4.00 kr per Ci.

(approx. 27 and 55 US-cents). This cost would also include the source moving mechanism.

5. Production Costs

An effective working year of 300 days has been assumed, corresponding to a plant utilization factor of approximately 84%.

Monomer: A 4 weight-% impregnation with methyl methacrylate has been used for these calculations, as mentioned in 2.1. To this figure 10% are added to cover handling losses. A cost of 3.00 kr/kg for methyl methacrylate has been used.

Co-60 replacement: For the source strength to be maintained at approximately the initial level, 13% of the initial loading must be replaced every year. The cost of this replacement Co-60 has been assumed equal to the initial investment cost, 2.00 and 4.00 kr/Ci.

Utilities: These costs include heating for the drying of the pipes prior to impregnation, electricity for pumps and cranes, water, etc. Drying costs are estimated at 12 kr per large pipe, or 87,000 kr/year, electricity consumption at 2500 kWh/day, or 100,000 kr/year, and water etc. at about 13,000 kr/year, in all 200,000 kr/year, corresponding to approx. 5.5% of the facility costs.

Operating labour costs: Labour costs are based on 4 1/3 shift per week, each consisting of two workers and one operator at 50,000 kr/year/man. Furthermore are added costs for 1/2 supervising engineer, i.e. 50,000 kr/year.

Health physics control: This comprises the processing of personnel and plant radiation monitors, periodic physical examinations and radiation surveys. A cost of 70,000 kr is assumed.

Maintenance and supplies: These costs are estimated at [illegible] of the initial facility cost [illegible] of concrete pipe [illegible]

<u>Depreciation and interest of facility</u>: A 10 years' depreciation for buildings and 5 years for equipment has been used at 12% interest.

<u>Depreciation and interest of Co-60 source</u>: A total of 15%/year has been assumed.

Production Cost for Large Pipes

Pipe size: 160 cm (64 inch) internal diameter x 200 cm (80 inch) length x 12 cm (4,8 inch) wall thickness.

Production capacity: 24 pipes/day for 300 days/year: 7,200 pipes/year.

Irradiation time: 24 hours.

Co-60 cost	2 kr/Ci	4 kr/Ci
Source strength	1.1×10^6 Ci	1.1×10^6 Ci
Source cost	2.2×10^6 kr	4.4×10^6 kr
Facility cost	3.6×10^6 kr	3.6×10^6 kr
Total investment costs	5.8×10^6 kr	8.0×10^6 kr

Production cost	10^6 kr/yr	kr/pipe	%	10^6 kr/yr	kr/pipe	%
Methyl methacrylate at 3.00 kr/kg	3.10	418	53.3	3.10	418	48.0
Co-60 replacement 13%/yr	0.29	40	5.1	0.58	80	9.2
Utilities	0.20	28	3.6	0.20	28	3.2
Operating labour cost	0.70	97	12.4	0.70	97	11.1
Health physics control	0.07	10	1.3	0.07	10	1.2
Maintenance and supplies, 8% of facility cost	0.29	40	5.1	0.29	40	4.6
Depreciation and interest, facility	0.76	105	13.4	0.76	106	12.1
Depreciation and interest, Co-60 source	0.33	46	5.8	0.66	[illegible]	[illegible]
Total production cost	5.74	784	100.0	6.36	870	100.0

Total annual production cost [illegible]

Additional cost for polymerization of concrete pipe [illegible]

Production Cost for Small Pipes

Pipe size: 30 cm (12 inch) i.d. x 200 cm (80 inch) length x 3.8 cm (1½ inch) wall thickness.

Production capacity: 168 pipes/day in 8 hour shifts of 56 pipes for 300 days/year: 50,200 pipes/year.

Irradiation time: 8 hours.

Co-60 cost	2 kr/Ci	4 kr/Ci
Source strength	1.5×10^6Ci	1.5×10^6Ci
Source cost	3.0×10^6kr	6.0×10^6kr
Facility cost	2.0×10^6kr	2.0×10^6kr
Total investment cost	5.0×10^6kr	8.0×10^6kr

Production cost	10^6kr/yr	kr/pipe	%	10^6kr/yr	kr/pipe	%
Methyl methacrylate at 3.00 kr/kg	1.37	27	37	1.37	27	30.5
Co-60 replacement 13%/yr	0.39	8	11	0.78	15	17
Utilities, 5.5% of facility cost	0.11	2	3	0.11	2	2
Operating labour cost	0.70	14	19	0.70	14	16
Health physics control	0.07	1	1	0.07	1	1
Maintenance and supplies, 8% of facility cost	0.16	3	4	0.16	3	3.5
Depreciation and interest, facility	0.47	9	12.5	0.47	9	10
Depreciation and interest, Co-60 source 15%/yr	0.45	9	12.5	0.90	18	20
	3.72	73	100	4.56	89	100

Total annual production cost	3.72×10^6kr	4.56×10^6kr
Additional cost for polymer impregnation of concrete pipe	73 kr/pipe ($[illegible])	89 kr/pipe ([illegible]/pipe)

6. Discussion

The evaluations in this report are very sensitive to a number of assumptions, such as the required radiation dose and the monomer content, and to some production parameters, such as plant utilization factor, irradiation time, cobolt-60 price, and production capacity.

The radiation dose required for complete polymerization and used in these calculations was based on experimental work. However, the possibility could not be excluded that on the basis of further research this dose could be reduced essentially, and consequently the cobolt-60 source strength could be reduced in the same proportion. A reduction of the radiation dose by a factor of for instance two would reduce the production costs for a large pipe, depending on the cobolt-60 price, by approximately 5 to 10%.

As it has been clearly demonstrated in the calculations, the monomer costs absolutely dominate the final costs. Therefore any reduction of the free-pore volume during the production process and consequently a reduction in monomer content - with unchanged strength properties of the final product - will be of special importance for the production costs.

The plant utilization has been assumed to be 300 days per year. Owing to the great fraction of the total costs which arises from the monomer costs, an increase in plant utilization to 330 days (10%) will only reduce the production cost per large pipe by approximately 3 to 4%.

As briefly mentioned in 2.3.4.1 the production costs will depend on the relationship between irradiation time, Co-60 source strength and Co-60 price. The following examples will illustrate this dependence. With the production capacity constant, an increase in irradiation time from 24 to 48 hours will reduce the total Co-60 source strength, but will result in a doubling of the number of irradiation holes. For a Co-[illegible] of 2 kr/Ci the increase in facility cost will [illegible] tion in source cost. For [illegible] however, the total [illegible] 10^6 kr (17%), and the [illegible] reduced by 6%.

Similar calculations for a reduction of the irradiation time to 8 hours show that the increase in Co-60 source cost is so high that in order to equal the reductions in building costs etc. a considerable reduction in cobolt price below 2 kr/Ci would be necessary.

A doubling of the production capacity to 48 pipes per day, with the irradiation time constant at 24 hours, will, owing to an estimated reduction in facility and operating labour costs result in a reduction of the production cost per large pipe of approximately 8%.

The purpose of this report has been to carry out a preliminary evaluation of radiation curing of concrete polymer material. As may be well known, an alternative method to the radiation curing is conventional thermo-chemical curing, initiated by chemical catalysts such as organic peroxides.

Without going into detail concerning the lay-out of a plant based on thermal curing it could be said that such a plant would still comprise the same facilities for drying and impregnation as described in this report. A rough estimate indicates that the costs of the chemical catalyst including facilities for heating the concrete pipes to approximately 80°C should be compared with the costs of the Co^{60} source.

Experimental data show that the amount of catalyst should be at least 2% of the methylmethacrylate weight, and as the price of benzoylperoxide is approximately 75 kr/kg, or 25 times that of methylmethacrylate, this would mean an additional treatment cost of approximately 200 kr/large pipe. This figure corresponds to the costs arising from the use of the Co^{60} source in the case of the highest Co^{60} price, namely 4 kr/Ci.

The process based on thermo-chemical curing could therefore not be expected to be more advantageous from an economic point of view.

7. Conclusion

As mentioned the costs of polymer impregnation of concrete pipes are first and foremost dependent on the consumption of monomer and on effective exploitation of the Co-60 source, i.e. they depend on the weight and wall thickness of the pipe.

The additional costs of Dkr 73 and 784 for polymer impregnation of concrete pipes, stated in the two calculated examples for pipes with a length of 2 m and with internal diameters of 30 and 160 cm, respectively, are based on optimal exploitation of the Co-60 source and an appropriately elaborated plant. With the present limited knowledge of the impregnation technique these figures must be regarded as an estimate of the lowest attainable additional cost. Using these figures, the total production costs of such plastic impregnated concrete pipes with strength properties of the same order as those of steel-reinforced pipes or pipes otherwise "refined", will in both cases be about three times higher than the costs of the corresponding unreinforced and untreated standard pipes.

As we find the same relative increase in production costs in both cases, we believe that on the basis of the principles of calculation presented in this paper, which have led to the design of suitable production plants for rather large and rather small pipes, it should be possible on the basis of further investigations, to design an optimal plant lay-out for other pipe dimensions or combinations thereof with a corresponding increase in production costs.

Under Danish economic conditions the improved strength properties of the concrete would allow an increase in production costs as compared with those for ordinary, untreated pipes, corresponding to a factor of about two.

The present evaluation was, however, only based upon an obtainable increase in strength properties, whereas an expected improvement of other properties, such as durability, tightness and resistance to chemical attack was not separately considered.

With a growing market need for corrosion-resistant pipes, e.g. for sewage and industrial waste water, it cannot be excluded that even considering the rather high production costs, the use of plastic-impregnated concrete pipes might become of interest also from an economic point of view in the years to come.

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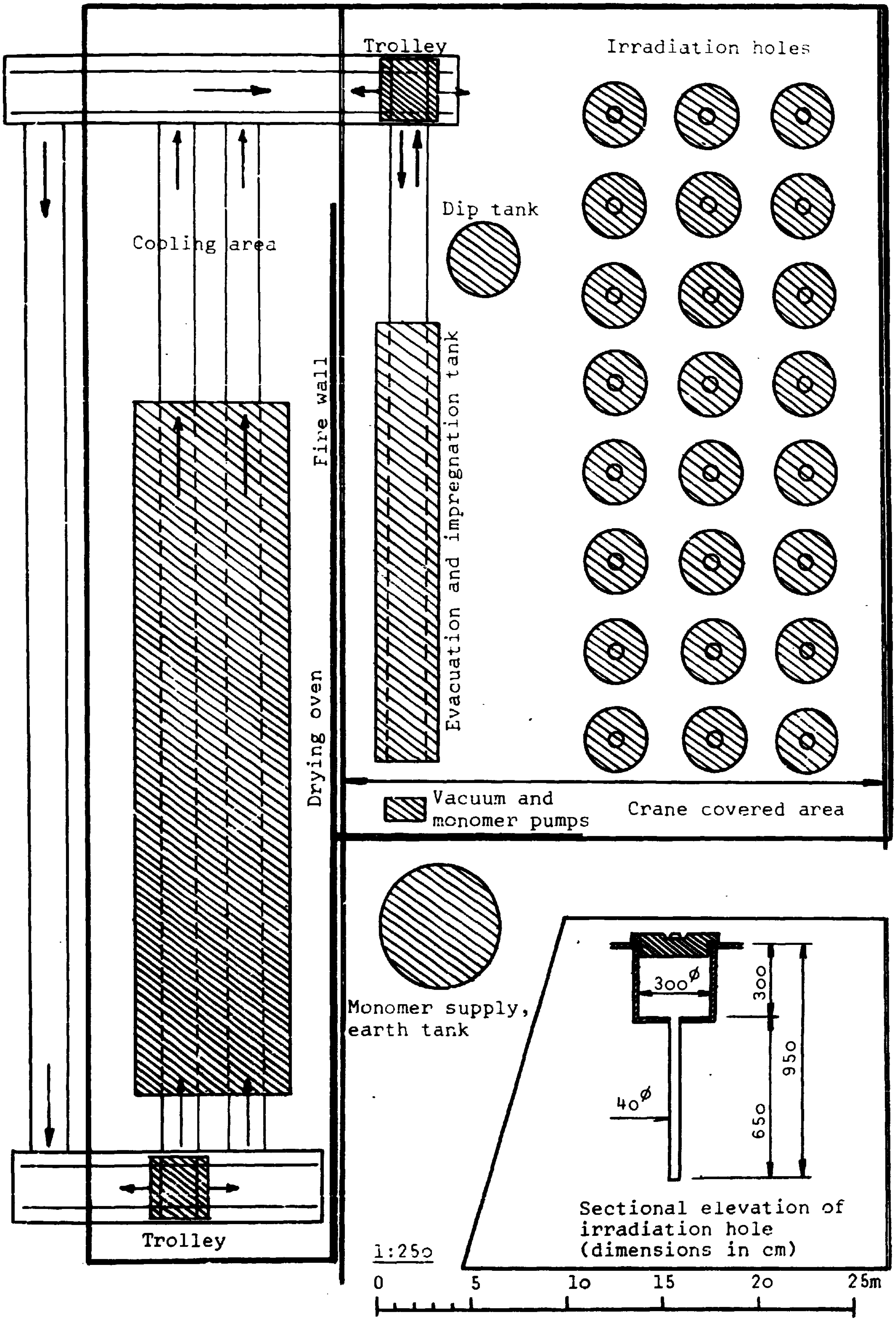

Figure 1. Plant lay-out for impregnation of large concrete pipes.

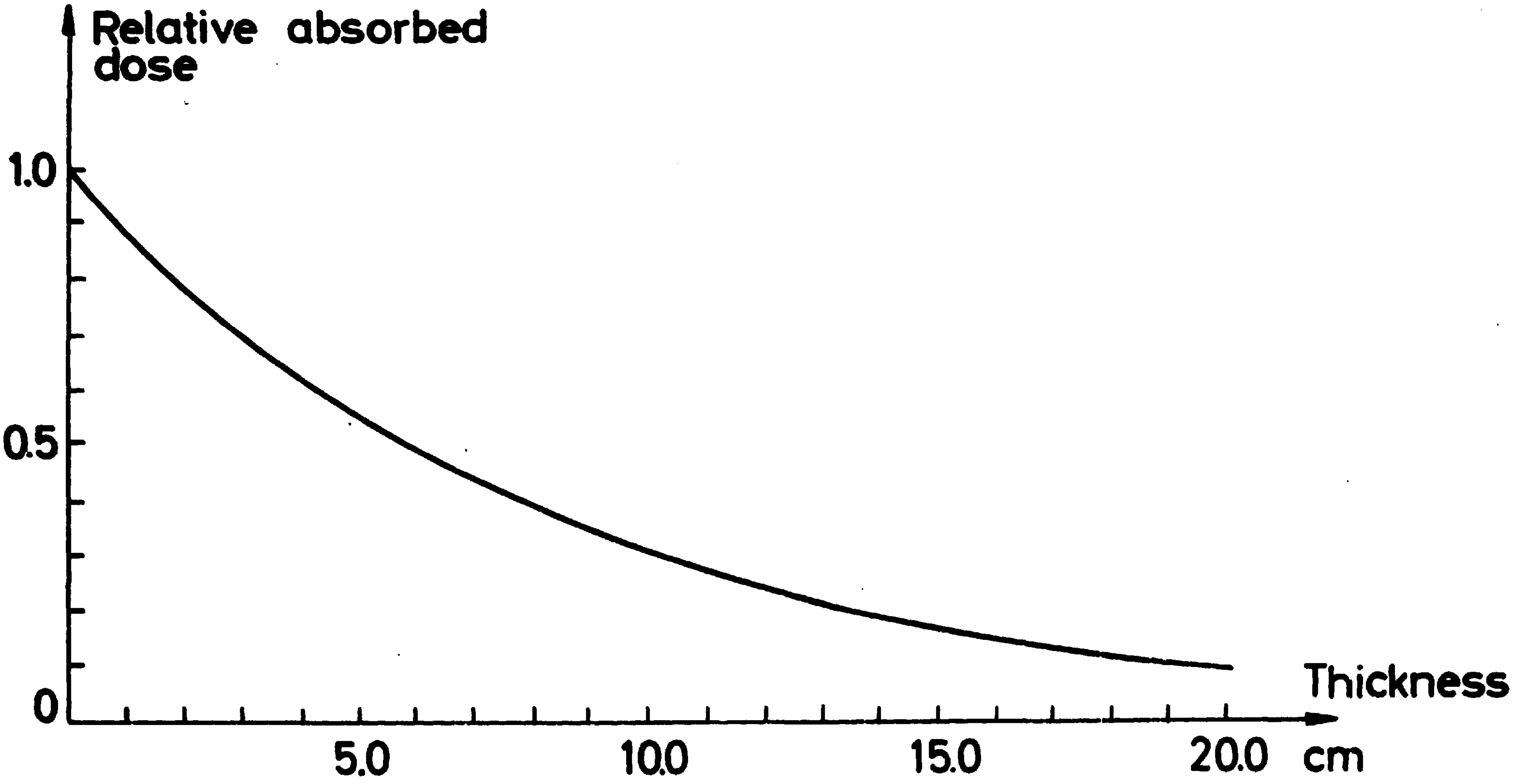

Figure 2. Relative absorbed radiation dose vs. thickness of concrete, ρ = 2.40 g/cm^3.

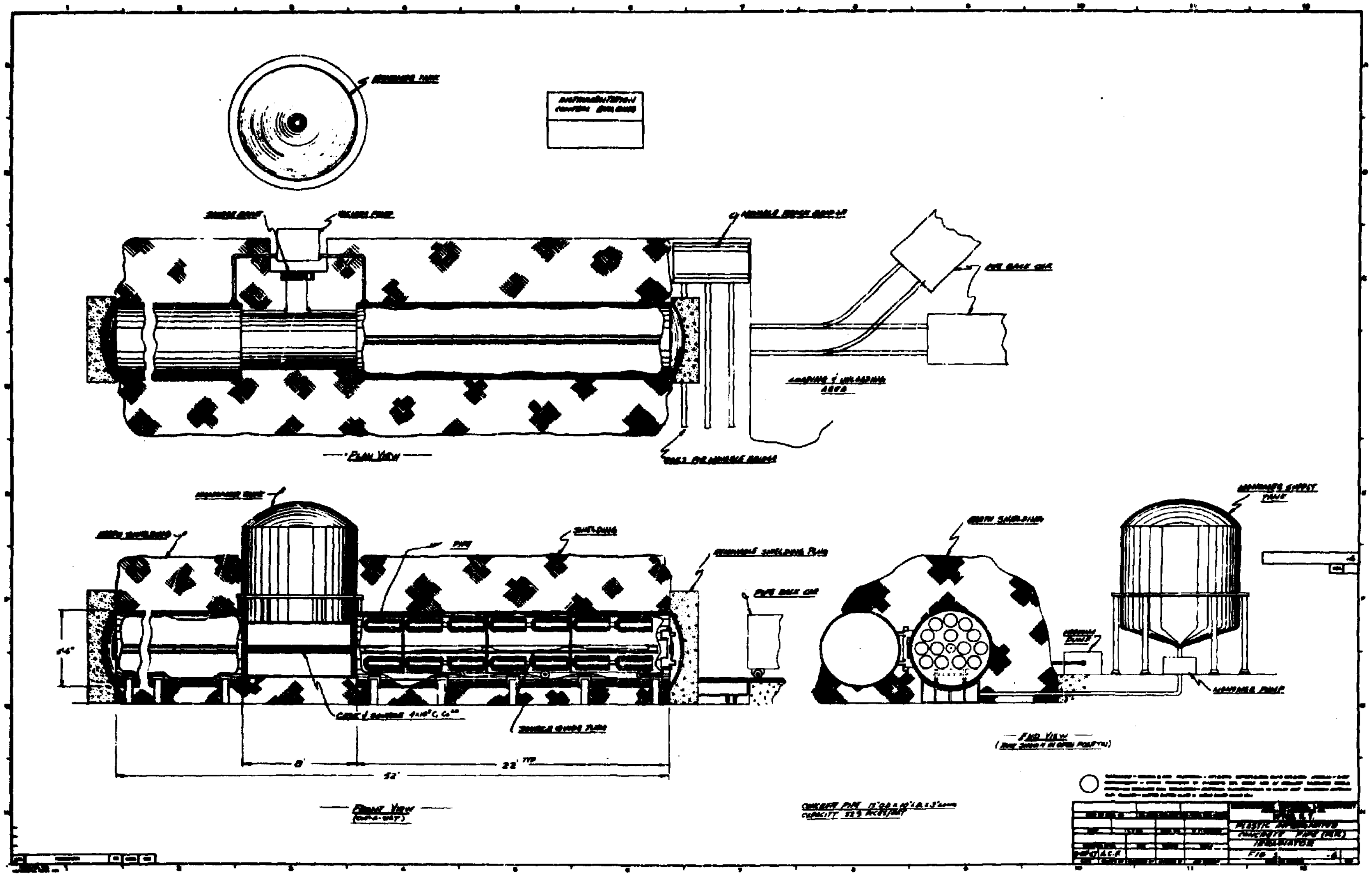

Figure 3. Impregnation and irradiation facility for small concrete pipes (from reference 1).

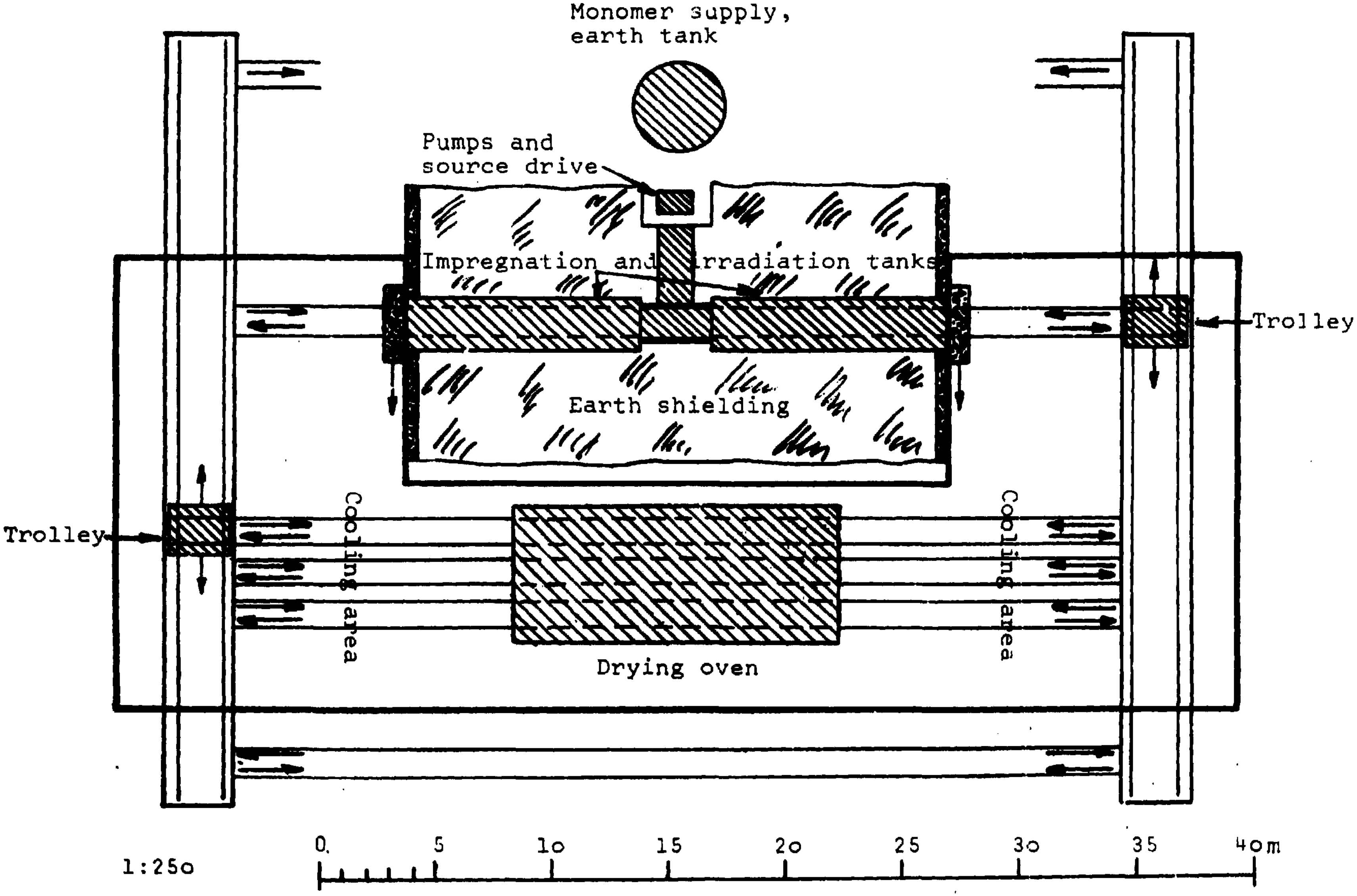

Figure 4. Plant lay-out for impregnation of small concrete pipes.