HYDROELECTRIC POWER RESOURCES
HVITA AND THJORSA RIVER SYSTEMS
SOUTHWEST ICELAND

Advisory Report

THE STATE ELECTRICITY AUTHORITY
GOVERNMENT OF ICELAND

HARZA ENGINEERING COMPANY INTERNATIONAL

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HVITA AND THJORSA RIVER SYSTEMS
SUMMARY OF REPORT

The State Electricity Authority
P.O. Box 40
Reykjavik, Iceland

Gentlemen:

We have completed our engineering study for the development of the Hvita and Thjorsa River Systems in Southern Iceland according to the provisions of our Agreement dated September 1, 1959. This Report presents our results. Our observations, conclusions and recommendations follow in eighteen Chapters and thirteen Exhibits. Chapter I sets forth those conclusions and recommendations which are general to the two river systems. Subsequent chapters present specific recommendations for projects.

Chapters II and III summarize background information on the two river systems. Chapter IV contains a general description of the Hvita River Basin and its proposed development. Chapters V to VIII then deal specifically with individual projects or groups of projects in various reaches of the Hvita. These are, in order, the Hestvatn Project, Hvitarvatn Storage Project, Blafell Reach, and the Gullfoss Reach.

Chapter IX contains a general description of the Thjorsa River Basin and its proposed development. This is followed by eight chapters dealing specifically with individual projects or river reaches. These are, in order, the Urridafoss Project, Thorisvatn Storage and Kaldakvisl Diversion, Upper Thjorsa, Tungnaarkrokur, Hrauneyjafoss, Lower Tungnaa, Upper Tungnaa and the Burfell-Sultartangi Project.

Chapter XVIII present our discussion of several smaller proposed projects on the tributaries or the main rivers including, in some cases, projects for which relatively little field information was available. Projects discussed therein include the Apavatn Storage and Dynjandi Project, Vordufell Pumped

Storage Project, Vatnsleysufoss Project, and the Selfoss Project in the Hvita River Basin; and the Skard and Haifoss Projects in the Thjorsa River Basin. Other possible smaller projects on the tributaries or on the main rivers were not reviewed by us.

Both past and future engineering investigations for the two river systems are aimed toward a "Master Plan" for the development of this great resource. It is our opinion, formed as a result of our field investigations and subsequent studies, that your Authority has taken important steps toward the development of such a Master Plan. Our recommendations are intended to serve as a general guide for its continuation and development.

It is evident that the greatest natural resource in Iceland is the potential hydroelectric power and energy of its rivers. Especially will the Hvita and Thjorsa Rivers bear importantly on the future of the nation. We have estimated that the hydroelectric potential of these two is about 2,500,000 kilowatts of power and 13,000 million kilowatthours of average annual energy. Less than five percent of this potential has been developed by the existing plants on the Sog River. The undeveloped potential on the Hvita River is about one-fourth of the total for the two river systems, but about six times that already developed. The remaining potential is in the Thjorsa River System.

We recognize that the formulation of a Master Plan for the development of the Hvita and Thjorsa Rivers will require several years and a rather large expenditure of effort and of money. Iceland must, in the meanwhile, provide additional hydroelectric power to meet its growing needs. Fortunately, there are several feasible projects on the Hvita and Thjorsa which, because of natural attributes, have a position in the Master Plan that is indicated rather clearly at this time. Accordingly, planning and construction can proceed immediately on one or more with assurance that each individual project will fit properly into the ultimate Master Plan.

We do not consider it essential that the master planning be on a full joint consideration of both systems. Each river system presents the potential of seasonal storage, moderately high head peaking plants, and lower head base load plants, and therefore each river can be considered as a separate entity. Consideration of the two rivers within a common master plan would have, at most, little additional effect on the development of each project therein.

Consideration should be given to carrying the master plan studies only to the point where one river system or the other may be selected for initial development. The Hvita River, among the two, has the advantage of easier access, closeness to load centers, favorable foundations, and projects of a size to permit the absorption of their production by the normal load growth in relatively brief time. The Thjorsa River, on the other hand, provides potential Projects of greater relative size more adaptable to serving large industrial loads, or future greater increments of normal load.

Our studies have not, in our opinion, revealed the probability of any truly unusual or serious engineering problems that have not been met and solved on similar developments elsewhere. Geologic complexities exist at some of the Sites and are associated principally with the Palagonite and Thjorsa Lavas. Geologic conditions of sites located in the older bedrocks appear to be excellent, generally. Natural construction materials appear abundant and of suitable quality near at hand to nearly all of the proposed sites. Construction diversion problems rate from normal to easy. There is not a single project which presents a serious or expensive access problem. Ice problems may, at times, become serious for brief intervals during operation at several of the proposed projects, but advanced designs and operational techniques may nearly eliminate them. Underground construction for the power features appear feasible at nearly all of the proposed projects, and may be an important construction and operation convenience, in consideration of the Iceland climate.

The undeveloped power potential of the Hvita and Thjorsa River Systems, is equivalent to that developed on the Tennessee River System in the United States by the Tennessee Valley Authority. The accomplishment of the development by your Authority will be no less spectacular and be of far greater importance to the economic future of Iceland than that of the TVA to the region it encompassed. We are proud to have participated in the furthering of the development of the Hvita and Thjorsa River Systems by preparing this Advisory Report.

Very truly yours,

Calvin V. Davis

Calvin V. Davis
President

TABLE OF EQUIVALENTS

Metric Equivalents

Metric Units		English Units
1 - meter (m)	equals	3.281 feet
1 - kilometer (km)	equals	0.6214 miles
1 - square kilometer (km^2)	equals	0.3861 square miles
1 - cubic meter (m^3) or		
1 - kiloliter (kl)	equals	35.315 cubic feet
1 - kilogram (kg)	equals	2.205 pounds
1 - million cubic meters	equals	811 acre-feet

Power Equivalents

1 - kilowatt (kw)	equals	1.341 horsepower
	equals	1000 watts

Electrical Definitions

Power . . . . Rate at which energy is produced or expended. Measured in kilowatts, watts, or horsepower.

Energy. . . . . Result of power acting for a period of time. Measured in kilowatthours. (kwh)

Annual Capacity Factor. . Ratio of the average power produced by the generators during the year divided by the peak amount for the year - expressed in percent.

Hydrological Definitions

Storage . . . . Reserve of water stored in lakes or reservoirs, and which can be released at a controlled rate. Measured in million cubic meters or thousand acre-feet.

Releases . . . . Controlled outflow from reservoir.

Yield . . . . Cumulative volume of water discharged by a natural stream over a period of time. Measured in million cubic meters or thousand acre-feet.

Regulation . . . . Adjustment of natural river flow by utilization of storage or pondage.

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CHAPTER I

CONCLUSIONS AND RECOMMENDATIONS

MASTER PLAN

The concept of a "Master Plan" to serve as a guide for the water resources development of a river basin, a region, or even an entire nation is now well recognized throughout the world. This concept has been followed by the State Electricity Authority (SEA) with respect to the Thjorsa-Hvita River Basins in Southwest Iceland. The value of the development of these two Rivers will be from the generation of hydroelectric power; all other values are relatively unimportant. Some incidental flood control benefit may accrue from the construction of storage reservoirs. The use of the two Rivers for domestic or industrial water supply, fisheries, irrigation, or commercial navigation cannot now be considered important.

An excellent start towards the development of a Master Plan for the two River Basins has been made by the SEA. The program of topographic and hydrographic mapping, geologic reconnaissance, and the obtaining of hydrologic data was well conceived and is proceeding rapidly. Most, if not all, of the major individual hydroelectric and storage projects have been recognized and engineering appraisal studies [1] have been made for a few. Minor projects obviously represent a very small portion of the rather short. Many of the proposed projects are complex geologically, and several seasons may be required to accomplish foundation explorations which would provide an adequate basis for design. The foundation conditions at certain other sites, on the other hand, are obviously so lacking in serious problems that one field season should be adequate to provide the required information for design. The selection of one of the latter sites for initial construction may save one or two years in achieving production. Easy access and a limited transmission distance also will tend to provide time savings. A relatively short construction period would also be important. The project should be of a magnitude that is in proper relation to the expected load growth, neither so large that it may take a number of years for its production to be absorbed, nor so small as to require another major project to be under construction at the same general time. A reasonable minimum of capital requirements, especially of foreign exchange, may also be very important.

The two proposed projects which appear to us to best fulfill the above criteria are Hestvatn and Urridafoss. The choice between the two appears to be dependent largely on the expected system load growth, which has been outside the scope of our studies. Hestvatn would be much the smaller of the two, but on the basis of recent historic load growth at Reykjavik, may provide adequate resources for two years or more.

Hestvatn could be in production in about three years time. The necessary field investigations are relatively very limited and could be readily accomplished in one summer season. Project planning and the preparation of construction drawings and specifications will require about six months. The physical construction could be accomplished within a period of two years. The transmission distance to Reykjavik or to a tie with the Sog plants is short. No major access problem exists with respect to the Hestvatn Project. Its position within the Master Plan appears clearly established, with the exception of the possible diversion of the Hvita to the Thjorsa above Urridafoss which may justify some consideration.

The Hestvatn Project would develop about 17 meter of gross head and the initial installed capacity would be on the order of 35,000 kilowatts. The average gross annual energy production would be about 280 million kilowatthours. The amount of this estimated power and energy which would be firm to load when considered as an addition to the existing supply system will require further study. That study may show justification for providing regulation at Apavatn and/or an initial stage at Hvitarvatn.

The Urridafoss Project meets most of the criteria established above in an almost equal degree with the Hestvatn Project. The construction period, however, may be about six months to a year longer. It is about three times as large a project and correspondingly more expensive from the capital requirements standpoint. Urridafoss would develop about 35 meters of head and the initial installed capacity would be about 100,000 kilowatts (without consideration of Hvita diversion). The average gross annual energy production would be about 740 million kilowatt hours. The relation of these power and energy amounts to the load will also require study. Regulation may be justified at Thorisvatn. A more limited initial installation may also be desirable.

None of the other proposed projects on the Thjorsa-Hvita System appear to present attributes with respect to early construction to a degree approaching equality with Hestvatn or Urridafoss. The time required for adequate field investigations and studies to establish position within the Master Plan appears to require a year or more longer with each. All are farther from the Reykjavik load center, more difficult of access, and have a more complex geologic setting, generally. Actual construction time of some may, however, be no greater.

Most of the criteria cited above for a plant to serve a normal system load growth apply equally to a large project constructed principally to permit the system to absorb abnormal power and energy loads. In addition, a relatively low unit-energy cost would be essential in order to attract one or more large industries which are power-oriented insofar as location is concerned. The inherent ability of the system to expand its resources rapidly to meet future increased load demands by such industries may also be important. This expansion might include incremental capacity at then existing powerplants, new powerplants, and/or additional storage.

The load of a large industrial plant or plants to be located in Iceland and supplied by system resources has, for purposes of discussion herein, been somehwat arbitrarily established as 200,000 kilowatts of demand and of firm continuous energy. A power and energy load of that general magnitude can be met with the addition to the system of either a single large project or of two or more smaller projects. The latter alternative will not be considered at this time. The only single project of adequate size is Burfell or the Sultartangi Alternative. Burfell appears preferable. The initial Burfell Project could develop 114 meters or more of head, depending on the selected reservoir level. The initial installed capacity could be about 300,000 kilowatts. A supply of energy equivalent to 200,000 average continuous kilowatts available nearly all of the time (95 percent or more) will require some storage located upstream, especially during the drier years (cyclic storage). The Thorisvatn Project, including the Kaldakvisl Diversion, appears to present the most attractive and adequate storage possibility for this regulation. Integration of Burfell within the then existing system may require somewhat less storage than if considered as an isolated project because of intersystem load and flow diversities.

The Burfell Project will require four years or more to place into full initial production. Field investigations and planning studies will require one year or more. The same is true for the Thorisvatn Storage Project. The physical construction of Burfell would require not less than an additional three years, while Thorisvatn could be constructed in about two years. We recommend proceeding with the field investigations and planning studies for the Burfell Project for at least the minimum purpose of making a comparison with the development of the Jokulsa a Fjollum on the north coast of Iceland.

The development of the Master Plan for the hydroelectric power development of the Thjorsa-Hvita Rivers will require the continuation by the SEA of general engineering investigations and studies, which are discussed in greater detail hereinafter. These investigations and studies should follow some general priority with respect to specific Projects or River reaches, or even with respect to each River System. In addition, more detailed investigations and project planning studies should proceed for projects now indicated for probably early construction.

We propose general priorities for future engineering approximately according to the following groupings of proposed projects:

Group I -

Hvita River Basin	Thjorsa River Basin
Hestvatn	Urridafoss
Hvitarvatn Storage	Thorisvatn Storage and Kaldakvisl Diversion
Apavatn Storage and Dynjandi	Burfell-Sultartangi

Group II -

Blafell Development	Upper Thjorsa
Gullfoss	Haifoss
Haukholt	
Vatnsleysufoss	

Group III -

Vordufell Pumped Storage	Hrauneyjafoss
	Tungnaarkrokur
	Lower Tungnaa
	Skard-Budafoss

Group IV -

Selfoss	Upper Tungnaa

(Small projects not previously studied)

The Group I Projects include those which we now believe hold the greatest promise for early construction as power or storage projects. Burfell is included principally because it is the only single large project. The remaining Groups are in the approximate order of attractiveness within our present knowledge. The Group III Projects in the Thjorsa River Basin all contain similar and somewhat complex geologic problems. No specific priority is indicated within each Group.

Consideration may be given to concentrating practically all effort on only one of the two River Systems; then proceeding to the second after the economic sites on the first are nearly fully developed. They are separate rivers and storage on one is not available for flow regulation at power-plants on the other, with the possible exception of the diversion of the Hvita to the Thjorsa above Urridafoss, the lowermost plant thereon. All major storage potential is located towards the headwaters of each Basin and would benefit power projects downstream therefrom.

The selection for construction of an initial project may tend to establish the River to be first developed. Storage thereon may be required as the second step in the development, and such storage would be utilized to enhance the economics of successive power projects or, alternatively, the power projects would share the storage costs. For example, initial construction of Hestvatn may require Hvitarvatn, which would be followed by power projects in the Blafell and Gullfoss reaches, all prior to any construction on the Thjorsa.

It may be advisable, as a first step, to carry the Master Planning Studies only to the point where a selection may be made between the two River Basins. The available financial and technical resources could thereafter be utilized more effectively than attempting to continue to spread them over the vastness of both Basins. The Hvita Basin has the apparent advantage over the Thjorsa Basin of nearness to load center, accessibility, simpler foundation conditions at potential sites, and projects each of a size which may be absorbed by normal load growth in lesser time. The Thjorsa Basin, on the other hand, is dominated by relatively large projects more suitable for large industrial loads, or greater annual normal load increases in future years.

The selection of a single Basin for development does not necessarily mean that no projects should be constructed in the other. The construction of an individual project in the second Basin may precede or come in between, in point of time, the construction of projects in the Basin selected for concentrated development. For example, Hestvatn might be followed by construction of a series of projects in the Thjorsa Basin.

FIELD INVESTIGATIONS

The field investigations which must be continued include topographic and hydrographic mapping, geologic studies, subsurface explorations, and hydrologic measurements and studies. Our recommendations for each type are presented below:

Topographic and Hydrographic Mapping

The program of topographic mapping on a scale of 1:20,000 with five-meter contours should be continued to include the area of all potential projects. It may be extended ultimately to include the entire area of both Basins outside the ice fields, but this is by no means necessary for the preparation of a Master Plan including only major projects. The priority of mapping should conform generally to the above Project Grouping and where the maps are not now available.

The area of each proposed project structure should be mapped at the proper time on a scale of 1:1000 or 1:2000 with one or two-meter contours, depending on local terrain. This rather detailed mapping for each project will normally not be required until definite Project Planning is undertaken. Even greater mapping detail may be required locally in the detailed design phase of each project. Such large scale mapping should not be required for the Master Plan Studies inasmuch as the 1:20,000 scale topography, supplemented in some critical places by profiles or cross-sections should be adequate. Some surveys for geologic mapping purposes primarily may be required. The mapping and survey requirements for each specific project discussed in this Report are, for the most part, discussed in the appropriate Chapter thereon. Route surveys for access roads and transmission lines will be required either in the Project Planning or Design Phases. These facilities may serve several Projects within any given general area. General reconnaissance and existing small-scale maps will serve adequately for cost estimates of these features in connection with the Master Plan Studies.

No additional general hydrographic surveys should be required. We understand that a hydrographic map of Lake Langisjor is under preparation by the SEA. Large scale hydrographic surveys, identical with the topographic surveys, will be required in the Project Planning and Design Phases of the engineering for some structures of most or all projects. This will include the lower portion of damsites, tailraces, outlets of tail-tunnels, submerged portions of intakes, canal entrances, etc. River cross-sections and stage measurements adequate to permit the determination of essential hydraulic data basic to backwater computations and for future reservoir silting surveys will be required for the detailed planning of some of the proposed projects, as discussed in the appropriate Chapters. In addition, these data will be required near the upstream end of any reservoir which may encroach on the tailwater of the next upstream project. All hydrographic surveys would be accomplished by soundings and must be correlated in location with the contiguous topographic surveys.

We believe that nearly all topographic surveys can be best accomplished by photogrammetric methods. These methods are now in use by the SEA, but a specific review thereof was not included within the scope of our assignment. We suggest that the review originally contemplated by the SEA in 1959 be accomplished. It is a rare instance in modern practice where photogrammetric surveys are not quicker, cheaper, and more accurate than terrestrial surveys. General accessibility and the absence of brush and trees makes Iceland nearly an ideal place for the use of photogrammetric survey methods. The proposed large-scale mapping (1:2000 or greater) will doubtless require additional photography from a lower altitude than now available.

Geologic Investigations

The excellent geologic reconnaissance accomplished to date by Kjartansson (2) should be continued to include the entire area of both River Basins, with specific reference to hydroelectric development. A general geologic map of the entire area is desirable ultimately but is by no means necessary for the Master Plan Studies. The detailed geologic investigations required for each project will provide a substantial amount of data for the overall understanding of the general geology of the entire area.

The specific geologic studies required for each project or for several closely situated projects are discussed and recommended in the appropriate Chapters. There is a general need for detailed geologic mapping of each project area, although this requires the availability of large-scale topography (1:20,000 or greater). It would include, initially, the mapping of areal geology, structure and stratigraphy. The stratigraphy would be expanded further as information becomes available from subsurface borings. Further geologic reconnaissance for sources of natural construction materials is required at every proposed project. These materials should be examined petrographically with respect to reactivity with the Icelandic cements.

Subsurface Explorations

Subsurface explorations are required at the site of each project proposed for construction and are of utmost importance. This work has barely been started and then for only a very few projects. The principal data to be obtained from subsurface investigations include water table levels, permeabilities, foundation strengths, stratigraphy, and construction material suitability. The methods may include percussion and rotary drill borings, auger borings, tunnels, drifts and shafts, test pits, trenches, bearing tests, and geophysical measurements; as each may be appropriate.

Percussion drilling will be the preferred general method of accomplishing borings in many formations and for some purposes. Wagon drilling or churn drilling may be used. Wagon drilling would be limited to water table measurement holes which would be entirely in rock and not greater than about seven meters deep. Churn drilling will ordinarily be the preferred boring method where core recovery is not important; through superficial materials; and through the softer bedrock such as some of the Palagonite and tuff; and through the harder bedrock such as the Thjorsa lavas where watertable information represents the principal information desired.

Samples should be obtained at frequent intervals from any soft materials which may form or be included within the foundations for structures. The samples should be preserved for standard laboratory tests and for examination. They should be as near to undisturbed as is feasible.

Nearly all holes should be preserved for purposes of groundwater measurements. These measurements should include more or less regular recording of the elevations of the groundwater table. Watertable levels downstream and, in some cases, laterally from each reservoir to determine the new conditions resulting from the construction will be important, and appropriate holes should be located and preserved with that ultimate purpose in view. Similar additional observation holes will be required as a part of the construction program. The rate and direction of groundwater movement will be important with some projects. Measurement may include dye, electrical, radioactive tracer, or other methods with some experimental tests required to establish which may be the most useful. A churn drill hole can be inexpensively preserved for groundwater measurements by inserting a perforated thin-wall tube prior to removal of the drill casing, with permeable sand and gravel placed in the annular space as the casing is removed.

Permeability information of subsurface formations is almost always of greatest importance with borings. Permeability tests should usually be accomplished in each bore hole (1) wherever drill water is lost, (2) at regular intervals normally not to exceed five meters, (3) at all changes in lithology, and (4) at such other times as the results of or the purposes for the drilling may indicate. The permeability tests should consist of water pressure tests wherever feasible, and universally with diamond core borings in rock. They may consist of (1) testing nearly the entire hole either progressively as drilled or upon completion, (2) progressive testing of the hole at intervals from the bottom and proceeding upward after drilling, and/or (3) testing segments of the hole, such as large open seams, by isolation with double packers.

The permeability tests wherever pressure testing is infeasible, such as is normally the case with churn drilling, may consist of pump-in or pump-out tests, bailing tests, or "slug" tests. These tests, for the most part, should be accomplished progressively as the hole is drilled and would include most or all of the open hole between maximum penetration and the bottom of the casing. The effects of these tests upon the adjacent watertable are frequently important and may require coincident observations in other nearby holes.

The permeability testing method to be used can be determined properly only at the time of drilling of each hole and to suit the conditions encountered or expected. The results obtained are of utmost importance to form the basis for and the estimated costs of any treatment program to assure the adequacy and safety of the structures of each project, and/or reservoir tightness.

The principal rotary drilling method recommended is the use of a diamond core drill. Drilling machines or methods which utilize drill "mud" are not recommended but might be used under some special conditions. The highly important permeability information from nearly all boreholes precludes the use of mud which tends to seal the drillhole walls in the formation. Diamond core drilling would be used for all holes where drilling observations and the core obtained will supply engineering information such as foundation strengths and stratigraphic detail. Nearly all borings at the site of proposed structures should be accomplished with a diamond core drill, especially if the formations consist of hard rock. Deepening of a borehole carried down to hard rock by churn drilling may sometimes be desirable. The drilling procedures should be variable to assure maximum core recovery and maximum information on rock characteristics wherever core is not recovered (lost). Water pressure tests should be accomplished for all diamond drill borings. The "NX" drill-core size is recommended with reductions to smaller sizes permitted only when required to permit deeper penetration. All core recovered should be preserved in appropriate core boxes to permit future inspection and study. Washings from "lost" core zones should be obtained and saved wherever feasible. Occasional core samples should be selected and laboratory tested. Samples should be obtained from overburden and from soft formations encountered, and preserved for appropriate laboratory tests.

Drilling and testing procedures outlined generally above for adoption in the subsurface exploration program for projects located in the Thjorsa-Hvita River Basin are presented in greater detail in References Nos. 3 to 7, inclusive, of the Bibliography. The laboratory tests of samples recovered by the drilling would all be of standard types and are not discussed in detail herein.

Shot drilling is not now recommended for any of the required subsurface explorations.

Tunnels, drifts and shafts of an exploration type are recommended for some of the proposed projects and are discussed in the appropriate Chapters. They would explore the bedrock formations of major underground structures, such as powerstations located in the softer Palagonite rocks. They would not be excavated until the preferred locations of the structures had been established by Planning Studies based, in part, on borings. They would be intended primarily to verify the site selection of the major structures and to provide more detailed information important to design. Specific information obtained may include tunneling characteristics, permeability relationships, strength of formations, etc. The position of each tunnel, shaft, or drift should be such as to permit its future incorporation into the permanent works for pilot bores, access, ventilation, power and control cables, or other useful purposes. Some tunnels or drifts may be required to permit in-situ modulus of elasticity tests of the foundation rock at proposed arch damsites. The cross-section of each bore would be minimal but should be ample to provide hand-working room. A minimum section of about three square meters is recommended.

Field bearing tests of relatively soft or yielding formations such as moraine or some of the Palagonite which may be proposed as the foundation for structures at some of the projects may be required to provide adequate information for design. Procedures which are more or less standard and described in Reference No. 3 of the Bibliography would be appropriate.

Test pits and trenches are recommended as most economical and practicable for obtaining some of the required subsurface information. They may be appropriate for the exploration of deposits of such natural construction materials as gravel, sand, moraine, soil, and lacustrine sediments useful for concrete aggregates or for fill dam construction. They would also be useful to explore the foundations for proposed structures where covered by or consisting of superficial materials, weathered or soft rock. Trenching is also frequently used as an aid to stratigraphic mapping, especially where the bedrock is covered by a thin mantle of superficial or weathered material.

Test pits are usually hand-excavated. Trenches may be excavated either by hand methods or by a bulldozer, or both.

Auger borings would also be used for exploration purposes. They would be especially appropriate for the exploration of soils, lacustrine, and similar deposits at the site of construction material sources or the site of such proposed excavations as canals. Hand augers and power augers may be used. The principal purpose of their use would be to determine the depth and characteristics of deposits and to obtain samples for laboratory testing.

Geophysical methods of exploration may have some limited application at some projects in the Thjorsa-Hvita River Basins. They may be used to determine the depth to bedrock under such superficial materials as moraine, and, perhaps, for some other applications. Either seismic or electrical resistivity methods may be attempted. Any utilization, however, requires confirmation of the indicated depth to bedrock by borings.

Hydrology

Modern methods of hydrologic measurements are presented in Reference No. 8. We recommend the following of the general procedures outlined therein.

The permanent automatic continuous stage recording stations already established by the SEA [9] in the Thjorsa-Hvita Basins are considered adequate in number and in location for nearly all basic hydroelectric planning purposes. Additional stations would provide more hydrologic information but are not specifically recommended at this time. We suggest that, if the SEA plans on the installation of additional stations, locations be considered on the Sanda River near Sandartunga, the Tungufljot near Sandvatn, the Stora-Laxa near Geldingatangi, and the Tungnaa near the most favorable site for a storage project in the upper reaches.

Reliable long-term discharge records represent the most valuable hydrologic data required for hydroelectric planning. This will require time in view of the short record for most of the established stations on the Thjorsa and Hvita Rivers. The accuracy from these stations would be improved by more frequent station attendance and discharge measurements. Access, especially in winter, presents the largest present problem and might be improved by the use of aircraft. Landing strips for light planes appear feasible near all existing remote stations. The use of a helicopter, which would be more expensive, would be even better.

The Master Plan Studies outlined in this Report will require the approximation of a long-term record for each River at each proposed Project Site. This can only be accomplished at this time by correlation studies. Some correlation records have been accomplished by the SEA at most sites. These, however, require continued re-evaluations as records become available from the newer stations located generally in central and upstream reaches, and from spot discharge measurements. As an initial step there is required a correlation record for each site for as long a period as feasible and with the record covering the same period for all projects in both Basins considered jointly.

Staff gages should be established at each proposed project and alternatives thereof, and a stage-discharge relationship established for each over as great a flow range as is feasible. Gages should be established at each proposed damsite, tailrace site, and proposed diversion point.

Automatic continuous stage recorders will be required as a part of each project when constructed. A few of these would be located at key points for some projects where required for reservoir level control and and would include automatic transmission of stage data to the powerhouse control room. Headwater and tailwater gages are normally installed at each powerstation. Automatic transmission of the stage data to the Master Station is required for a remotely controlled plant.

The evolving of design flood hydrographs will be required, ultimately, for each proposed project as a guide to spillway capacity design. Actual flood discharge records are few for either River. We recommend that a hydrometeorological study be accomplished for the two Basins considered jointly.

The movement of underground water is an important consideration at some of the project sites, particularly those associated with the Thjorsa lavas, and is discussed in more detail in the appropriate Chapters. The watertable information will be obtained from the observation wells discussed above and from field measurements of the level at springs. Measurements of the rate and direction of underground movement has been discussed above. Quantitative measurements must be based largely on discharge measurements of individual springs where appropriate. These measurements should be made under varying meteorologic and hydrologic conditions to include all seasons, precipitation, and stream discharge conditions. Post-construction measurements of springs and of the watertable away from the reservoir will be important for many of the projects. It is doubtful that chemical analyses will give any reliable clue as to the source or movement relationship of groundwater at any of the proposed projects, but radioactivity analyses may possibly be of some limited purpose.

The sediment carrying characteristics of the glacial and draga rivers will be important to the design of projects located thereon. The program of silt measurements should be continued. The transportation of sediment varies considerably with the discharge. This is especially true of the movement of the heavier particles along the bottom of the river, which takes place principally during high flows. Special samplers have been developed for measuring bedload movement as described in Reference No. 10 of the Bibliography.

An attempt should be made to establish the relationship between sediment transportation and discharge at important locations in the Thjorsa-Hvita River System, such as Gullfoss and Hestfjall on the Hvita, Nordlingaalda and Burfell on the Thjorsa, Saudafell on the Kaldakvisl, and Tungnaarkrokur on the Tungnaa River.

The measurements of silt trapped in some of the reservoirs should be made after construction thereof. This will require the establishment of silt measurement ranges prior to construction, and field measurements of each on an annual or longer basis thereafter. The reservoir measurements might be made with a fathometer. The measurements may be useful principally to provide data for the design of subsequent projects.

The operation of projects located on the Thjorsa and Hvita Rivers can be improved on the basis of meteorological data made available from within the Basins, especially as the two Rivers become more fully developed by storage reservoirs and higher-elevation power plants. The present recorded meteorological data is, for practical purposes, nonexistent. The sources of data can be improved by the establishment of additional snow courses and meteorological stations.

We recommend the establishment of at least two snow measurement courses near the headwaters of each River. Those on the Hvita Basin should be in the general vicinity of Hvitarvatn but at significantly different elevations. Those on the Thjorsa Basin additional to the two now existing should be located near Nordlingaalda on the Upper Thjorsa and near Vatnaoldur on the Upper Tungnaa. A third course near the mouth of the Tungnaa would be desirable. Consideration of locating the snow courses near stream gaging stations to facilitate measurements may be given. A few years of records from these courses correlated with subsequent runoff measurements may show the need for additional courses located at higher elevations.

The location of meteorological stations to obtain records of temperature and precipitation in by far the greater area of both Basins is handicapped by the lack of habitation. We recommend that the "cooperative observer" type of meteorological stations be established at ten or more locations in the inhabited areas and especially at the most outlying farms. A higher type of station should be established at all projects where operators will be stationed and beginning with the initiation of construction. All field parties resident for a few weeks or longer on field investigation programs should be equipped with instruments and encouraged to obtain temperature and precipitation records. The establishment of automatic recording temperature and rainfall instruments at remote locations such as near the stream gaging stations is desirable but is not recommended for installation at this time.

ICE PROBLEMS

The development of designs to provide the most practicable solution to the ice problems expected at the proposed Projects in the Thjorsa and Hvita River Basins will require much additional study. These studies may include:

1. A development of the understanding of the physics of ice formation as it may relate to each Project;
2. A thorough review of the technical literature pertaining to ice problems;
3. Obtaining of specific hydrologic data;
4. Field inspection and analyses of operational results at Projects where special provisions have been installed; and
5. The development of special designs.

It is generally recognized that surface ice is formed on still or slow moving water by overcooling of the top layer. When the ice is formed the rate of increase in thickness becomes gradually slower because the heat loss is reduced by the ice. The surface ice on natural rivers is often broken up during changes in flow and/or weather and is transported downstream in large sheets and blocks of ice. This may become a problem on some of the reservoirs.

The formation of subsurface ice such as frazil and anchor ice is, according to the latest theories[11], the result of (a) overcooling of the water, (b) intensive radiation, and (c) conduction to the air of the released heat from the ice formation process. The presence of crystalization cores is required to trigger the process. The beneficial effects of a solid ice cover on canals and natural streams in preventing subsurface ice formation has long been recognized and the reasons for it are easily explained by the above theory. It is also well known that the formation of subsurface ice is promoted by rapids and open shallow river sections where conditions are favorable for overcooling of the water and the conduction of heat. Subsurface ice of this type including sludge ice formed by snow blown into the open water will probably present the most serious ice problem to be encountered at most of the proposed Projects.

It is important to recognize that the regimen of the river through the reservoir and downstream from the dam and from the tailwater may be changed drastically from natural conditions, insofar as ice formation is concerned, by the construction of each Project. Further modifications may result from the creation of additional Projects in each Basin.

Ice problems may be reduced with a large and deep reservoir. This is generally accepted as a good arrangement which has been successfully employed on many projects. The reservoir will be covered by ice in cold weather and this will not only prevent the formations of frazil and anchor ice but sludge ice entering the reservoir may melt before it reaches the intake. A solid ice cover will also prevent snow from mixing with the water. Topographic and economic considerations do not always permit the creation of such a reservoir. Additional reservoirs constructed at upstream locations will also tend to reduce ice problems.

The provision of lowflow velocities upstream of the power intake to permit the formation of a protective ice cover is usually beneficial. Approach sections to the intake should be made deep and large enough to obtain the desired velocity. The maximum velocity will depend on local weather and ice conditions but it should probably be less than one meter per second. The station flow may be shut off temporarily or reduced in order to start the formation of surface ice. Alternatively, a temporary raising of the reservoir may produce the equivalent result. An intake located as deep as is feasible is generally recognized as desirable.

An optimum hydraulic arrangement of the spillway and intake is essential. The intake should be located upstream from and nearly normal to the structure containing the spillway gates and the ice sluices. This arrangement is frequently combined with booms or skimmer walls as discussed in References Nos. (11) to (15), inclusive. Opening the gates creates a downstream current which transports the ice past the intake and over the spillway, but may require some aid by hand or mechanical means. Skimmer walls are usually submerged only one or two meters below the reservoir level and this is normally sufficient to permit removal of most of the ice flowing on or near the surface. Ice thrust must be considered in the design of these structures.

Heating of trashrack, gate guides and other metal parts at the intake and the dam is commonly used to prevent frazil ice from adhering. Release of air bubbles and heating with infra-red light have been used in front of intakes, gates and skimmer walls to facilitate removal of surface ice. Trashracks are sometimes completely removed with large turbines and with little or no debris in the water. Steam or electric heating of the turbine pit may be required in order to prevent icing of the runner, wicket gates, or guide vanes.

It is not to be expected that the ice problem and the most practicable solution thereof will be the same at each Project in the Thorsa and Hvita River Basins. Special studies and designs will be required for each Project.

A program consisting of some measurements and correlated observations may possibly provide basic data helpful to future powerplant design and operation. Water temperature measurements should be obtained during the winter season at as many places and as often as is feasible. These measurements should be correlated with air temperature, silt measurement records, and general observations of local icing conditions, and would permit study and analyses to establish interrelation criteria possibly useful for future operations. For example, an interrelation which shows the possible imminent development of serious ice conditions may permit a plant operator to alter reservoir levels and/or velocities to reduce difficulties.

SYSTEM OPERATION STUDIES

A series of System Operation Studies will be very important to the development of the Master Plan for the Thjorsa-Hvita River System and for each individual project thereof. The Operation Studies will provide, for each project, a principal basis for the selection of both initial and ultimate installed capacity, the amount of head to be developed, and, where appropriate, the amount of seasonal storage to be provided both initially and ultimately.

A considerable amount of data is required to form the basis for the proposed System Operation Studies. Unregulated flow data on not greater than a monthly average basis will be required for each project or projects considered for a particular Study, and for the longest feasible period. These data would be supplied in major part by the Discharge Correlation Studies discussed above. The overall period would need to be identical for all projects and should include wet, dry, and average years. The gross net head potential at each Power Project and the storage potential at each Storage Project would need to be established. The magnitude and variation of the power and energy loads, including station use and losses, for each

System under study would need to be estimated. The Power Market Study would provide the bases for the load estimates. The evaluation of the results of each System Power Study in its relation to plant characteristics in order to evolve the optimum initial and/or ultimate development for each Project will require appropriate estimated Project Cost Data for the ranges of head and installed capacity inherent for each.

Each System Operation Study requires a multitude of detailed but basically routine computations. These computations may be accomplished manually but would require several computers for many weeks of time. All of the studies under consideration can be accomplished more expeditiously and less costly by the utilization of an electronic computer of adequate capacity. We recommend the use of a computer such as the IBM 650 or Bendix G-15. The major skill required is in the computer programming.

The development of the Master Plan in more or less final form will require System Operation Studies which would consider all or nearly all of the proposed projects of the Master Plan to be within the System. Each Study might include one or the other of the development alternatives for individual projects discussed in the Chapter appropriate thereto. In view of the many development alternatives worthy of study with each of the several Projects and the wide range of installed capacities which should be considered, it can be seen that a large number of individual Operation

Studies are required in order to evolve the optimum plan of development for each Project and for the overall System considered as an entity. Inasmuch as it may require several years to develop all of the data required for the ultimate Master Plan, earlier Operation Studies would need to be based on either approximate data for some Projects or a somewhat less than complete System.

We have indicated above that one or more Projects may be required to be in operation within the next few years and that their general position within the Master Plan is indicated in reasonable degree at this time. A series of Operation Studies will be required with each new Project considered as an addition to the then existing System. Similar studies would be accomplished thereafter not later than the time of definite Project Planning thereof. For example, with Hestvatn selected as the next Power Project, the initial operation studies would consider the existing Sog System plus Hestvatn; then the next series might include the Sog Plants plus Hestvatn plus Hvitarvatn. These studies would provide the bases to establish the initial head, capacity and storage provisions; ultimate provisions would require Operation Studies for the overall Master Plan.

CONSTRUCTION MATERIALS

The natural construction materials required for the types of construction proposed for the various Projects of the Master Plan may include coarse and fine concrete aggregates, filter, rock-fill, rolled-earth fill including impervious core, road metal, and pozzolan. Possible sources for each proposed Project are discussed in the Chapter thereon.

Sand and gravel deposits represent one basic source of construction materials. They include stream deposits, eskers, and deposits along ancient shorelines. The stream deposits are of sand size and smaller with only a minor amount of gravel. They are associated with the present streambeds and floodplains. There is one known large splay of coarse gravels below Tungnaarkrokur. Eskers are few and are probably all located higher than elevation 300 meters. The only major one observed by us was located southeast of Blafell, and supplemental photo reconnaissance failed to reveal any others. Ancient shorelines deposits appear widespread at about elevation 100 meters in the lower portions of both Basins.

Basalt flows of the Thjorsa lavas, Hreppar Formation and of the Grey Basalts represent major sources for rock-fill and manufactured concrete aggregates and filter materials. Flows of one Formation or the other occur not far from nearly every Project site. They are all flat-lying, moderately thick, and thus favorable for quarry development where not covered by heavy burden. The more glassy phases of the Palagonite Formation are not considered suitable, as a general rule, for these purposes.

Possible deposits of impervious core and rolled-earth fill materials exist in ancient drained lake beds, present streambeds, moraines and the soil cover. The lacustrine sediments are associated with old lava-dammed lakes, most or all associated with the Thjorsa lavas; deposits were observed upstream and downstream from Tungnaarkrokur, adjacent to the Thjorsa upstream from its confluence with the Tungnaa, the upper reach of the Rauda, and the lower reach of the Fossa. The recent stream-bed and floodplain deposits tend to be granular and consist of silt and fine sand sizes. Nearly all are saturated. The morainal material is wide-spread above about the 300 meter level but absent at lower elevations, generally. The pumice-rich loessic soil is common below but not above about the 250-meter level. It may represent a source of pozzolan, locally.

Volcanic cinder and scoria, represent an important and widespread source of road metal. Crushed rock, including Palagonite, and solifluction products may also be used.

It is our opinion that suitable natural construction materials are present within reasonable haul distance of all Projects, except possibly those on the Upper Tungnaa. The design of many of the Projects will be determined basically by the nature of the materials available nearby. Appraisal estimates can assume, for the most part, the availability and suitability of these natural materials. Field reconnaissance with regard thereto must be a continuing matter. Detailed reconnaissance, sampling and testing will be appropriate to the definite project planning and design phases of each Project. Standard methods of sampling and laboratory testing are appropriate and will not be discussed in detail herein.

Some large scale field tests may be required at the appropriate time. Test blasts may be desirable to determine the nature of breakage of the rock from tentatively selected quarry sites. This may also be followed by crushing and screening of samples up to several tons in weight to check on the possible use for concrete aggregates. Relatively large scale compaction tests may need to be conducted in the field of possible core and rolled-earth fill materials, and would require equipment of nearly the same size and capacity as would be used in the actual construction. These field tests may include the blending of two or more basic types of materials.

ESTIMATED ENGINEERING COSTS

We have prepared an approximate estimate of cost for the more or less specific recommendations presented in this Report. The estimate is intended to include only the investigations of an initial nature as presented in the appropriate Chapter for each Project. Studies of a nature which are general to one or both River Basins are also included.

The investigations may, in general, be divided between Master Plan appraisals and, for a few Projects, more definite project planning studies. The estimates include:

1. Topographic and hydrographic mapping including both the field work and map preparation.
2. Geologic mapping and foundation investigations. This includes also construction materials investigations and laboratory tests and analyses.
3. Hydrologic field work and office analyses.
4. Planning studies basic to such reports as appraisal, Master Planning, and definite project plans, as appropriate.
5. System Operation Studies, including Power Market Studies.

The costs are expressed in dollars (U.S.), but on the basis that the field work and much of the office work will be done in Iceland. There is included some allowance for the use of foreign consultants. Our cost estimates are summarized on Exhibit 1. It must be recognized that the estimates are approximate, and costs of the actual work accomplished ultimately for each Project may vary substantially therefrom.

CHAPTER II

INTRODUCTION

AUTHORIZATION

The State Electricity Authority (SEA), an Agency of the Government of Iceland, retained the Harza Engineering Company International to provide engineering services in connection with development for hydro-electric power of the Thjorsa and Hvita River Systems in Southern Iceland. The original Agreement No. F 10/T 43-22-087-90012 was signed on September 1, 1959. A Supplementary Agreement, dated September 15, 1959, provided the basis for compensation to the Company for supplementing, extending and completing the studies and recommendations required under the original Agreement.

The Agreements required our Company to make a professional study of the preparations for the development of the hydroelectric power potentialities of the two River Systems carried out to that data, and to give recommendations for the continuation of those preparations. These services were divided into three closely related Phases:

Phase a required a critical study of the preparatory work which had been carried out and of the work envisaged by the SEA. It included a study of the descriptions and drawings of projects already suggested.

Phase b included visits to the suggested power sites and a surface examination and engineering appraisal of the topographical, geological, and hydrological conditions at each site, and of the natural construction materials available in the vicinity thereof.

Phase c is our recommendations as presented in this Report. This Report includes recommendations for: (1) the general investigations and studies required for harnessing of the water powers of the two River Basins; (2) the further field and office investigations required for each project, including suggested alternatives; and (3) the organization and arrangement of such investigations together with an approximate cost estimate of the recommended investigations.

FIELD STUDIES

Phases a and b were carried out in Iceland in September and October, 1959, although more detailed analyses of the work under Phase a continued through the subsequent office studies.

A field reconnaissance was made of the Hvita and Thjorsa River Basins during the month of September 1959 by Messrs. C. K. Willey and A. R. Engebretsen, engineers, and J. Hoover Mackin, geologist, all of our Company. Potential sites in the Thjorsa River Basin were inspected during the week ending September 20, and the Hvita River Basin was visited the following week. All major sites in the two Basins were reconnoitered except one each on the Upper Thjorsa and the Upper Tungnaa which were difficult to reach because of the late season, and the Skard Site. The inclement weather of that period, however, did not affect the reconnaissance in any serious degree. Reports and basic information on geology, hydrology, topography and planning were made available, but the lateness of the season did not permit a comprehensive study of that information prior to the field reconnaissance. It was therefore of great benefit to us that several Icelandic engineers and geologists, familar with the field investigations and engineering studies accomplished and planned, participated in the reconnaissance. Subsequent conferences and discussions in Reykjavik with engineers and officers of the SEA clarified many points important to the understanding of particular problems associated with hydroelectric development in the two Basins.

The data obtained in Iceland and transported to the United States was of great importance to the subsequent studies.

OFFICE STUDIES

The office studies basic to the conclusions and recommendations of this Report required by Phase c were carried out in Chicago, principally by the same company personnel who had accomplished the other two Phases in Iceland. The guide to the overall plan of development as well as that to each of the proposed projects within the plan was evolved on the basis of thorough examination and analyses of the reports and data obtained from the SEA, and with the benefit of personal knowledge of most of the project sites.

It was not possible for us to carry out our studies to the same degree of completeness for all proposed projects in the two River Systems. The available amount of basic information varied considerably from area to area and from site to site. A very limited appraisal only was feasible for a few of the proposed projects. The relatively greater available data permitted more detailed study of most of the larger and more important projects. Alternative plans previously proposed were, in some instances, either included or eliminated on general grounds based on judgment principally, but with care so as not to jeopardize the evolution of optimum layouts and plans.

Our studies were, as a general rule, carried out primarily with a view to establishing the basis for recommendations relative to future field and office investigations and studies. Important factors such as foundation geology, streamflow, storage requirements, topographic relationships, natural construction materials, general access, and the element of time for engineering and construction were given consideration in as much detail as was feasible. This Report, which represents the results of our reconnaissance, studies and investigations, is aimed to provide the basis for evolving utimately a "Master Plan" for the development of the hydroelectric power resources of the Thjorsa and Hvita River Systems and which will also permit the SEA to proceed with the engineering and construction of individual projects as required with assurance that each will, from its inception, fit properly into that Master Plan.

The English spelling has been used for some of the place names referred to in this Report. Icelandic letters or syllables in these names and which have no English equivalent have been replaced by English letters or syllables with the same or nearly the same phonetic sound.

PREVIOUS ENGINEERING WORK

General.

The growing power and energy load including that for needed industrial expansion now requires the development of new hydroelectric resources in Southwest Iceland. The construction of hydroelectric power generation facilities has up to the present time been concentrated on the Sog River, a tributary to the Hvita. A total of about 100,000 kilowatts of capacity have been installed in three powerplants thereon during the last 25 years. The Sog potential is now exhausted, except for incremental capacity, and extensive investigations have therefore been carried out over the last several years in order to obtain the basic data for planning the further development of the large potential in the Thjorsa and Hvita River Basins. This work is being co-ordinated by the State Electricity Authority and includes general mapping of large segments of the two River Basins, more detailed mapping of potential power or storage sites, geologic surveys including subsurface exploration by drilling, and hydrologic and hydrographic measurements and studies. Office studies for the appraisal of a number of specific projects have been carried out concurrently with the field investigations. The engineering accomplished to the time of our field reconnaissance is summarized hereinafter.

Topography

The small scale maps of Iceland include the entire area of both River Basins. They include the Danish Geodetic Maps on a scale of 1:100,000 and the United States Army Maps on a scale of 1:50,000. Both maps have a contour interval of 20 meters. Elevations taken from these maps may vary locally by up to about 10 meters. These maps were very useful for our field reconnaissance and subsequent studies, but their lack of detail prevents them from serving for more than a very preliminary appraisal of hydroelectric potential. They were the only topographic maps available for large segments of the two Basins and including the sites of some of the proposed projects.

Most project sites and contiguous areas were, however, also mapped to a larger scale with more detail by the SEA in recent years. Exhibit 2 shows the extent of aerial photography and of topographic mapping of the two River Basins as of October, 1959.

Photogrammetric methods have been used extensively for the large scale mapping, and the work is progressing rapidly. The major part of the Tungnaa River Basin and the Thorisvatn and Upper Thjorsa areas have been photographed and provided with ground control. Maps on a scale of 1:20,000 or 1:5,000 with five and two-meter contour intervals, respectively, have been prepared for some potential project sites within these areas. Only minor additional topography remains to be prepared for appraisal and planning purposes, except for the Upper Tungnaa region. The Haifoss, part of the Burfell, and most of the Skard-Budafoss Project areas have also been photographed but, except for the Haifoss region, ground control is not yet established. The lower reaches of the Thjorsa have not been covered by the aerial survey, but terrestrial surveyed maps on a scale of 1:5,000 with a 2.5-meter contour interval are available for most of the Urridafoss Project area.

No aerial photography has been accomplished in the Hvita River Basin. It was intended that the area should be flown last summer, but bad weather prevented the realization of the program. Excellent terrestrial surveyed maps are available, however, for the Hvitarvatn-Blafell region and for the Gullfoss Project Area. With minor supplements these maps are adequate for planning purposes. The Blafell topography is on a scale of 1:10,000 with five-meter contours, and the Gullfoss area is mapped on a scale of 1:2,000 with a two-meter contour interval.

The SEA has also surveyed and prepared large scale profiles of both Rivers and their principal tributaries. A complete profile is available for the Hvita and also for the Thjorsa, Tungnaa and Kaldakvisl Rivers, except for their uppermost reaches. Important sections of the Tungufljot, Bruara, Stora-Laxa and Fossa Rivers have also been profiled. These profiles are extremely useful, and provide valuable data for the appraisal of hydroelectric potential, especially in the areas where the detailed mapping is not yet complete.

Hydrology

The hydrological work accomplished by the SEA up until 1959 is summarized in a report by Sigurdjon Rist and Jakob Bjornsson, dated June 1959.[9] This Report was an extremely valuable source of engineering information for our studies. It contains not only factual hydrological data on the two River Systems, but also correlated flows, duration curves, flow regulation curves and other computed and descriptive information. We have not made a systematic check of the information given in the Report, but the methods used appear to be well conceived and the analytical treatment carefully executed.

A great effort has been made by the SEA during the last few years to obtain the hydrologic data required for the appraisal and the planning of the hydroelectric development of the two River Basins. Apart from the Sog River where streamflow records are available since 1939, a systematic hydrologic survey of the area began in 1947 with the installation of automatic continuous stage recorders on the lower reaches of the Rivers. Five gages were installed on the Hvita and one gage on the Thjorsa between 1947 and 1951. Two additional stations were established on the Hvita and seven on the Thjorsa in 1958 and 1959. Stage recorders have thus now been installed at all important locations throughout the two River Basins. The work has been well executed, and in a few more years, the records should provide a fairly reliable basis for the computation of natural streamflows. At the present time the streamflow records are of somewhat short duration for planning purposes, especially for the Thjorsa River System, but this deficiency will gradually diminish as more records become available.

A study of old records on large floods was made by Rist in 1959 as a guide to determining design flood hydrographs. His findings are presented in a supplement to the SEA Report.

Precipitation measurements are meager within the River Basins. Only two stations are in operation, Eyrarbakki on the coast near the Hvita (Olfusa) River and Haell about 50 kilometers inland at 100 meters altitude.

No continuous measurements are available for the interior regions. Two snow courses were installed in 1958 in the upper part of the Thjorsa Basin with a view to establishing a correlation of the water content of the snow and the subsequent discharge from snowmelt.

Sediment measurements and chemical analyses of the water of the two Rivers have been carried out, the results of which are presented in the SEA report.

Geology

The geology of large areas within the River Basins have been reconnoitered by Gudmundur Kjartansson, geologist with the Museum of Natural History, Reykjavik, and is described in his Report to the SEA dated August 1959. [2] The principal regions covered by Kjartansson are the Thorisvatn, Langisjor, Sultartangi-Fossa and Urridafoss areas in the Thjorsa Basin, and the Hvitarvatn and Blafell areas in the Hvita Basin, with particular emphasis on previously proposed dam and tunnel locations. The Report was of much value to us during our field reconnaissance and for our subsequent studies. It gives an excellent introduction to the general geology of the River Basins in addition to specific information on the sites of some proposed reservoirs, dams and tunnels.

Some additional geologic information, attributed to Kjartansson, for the Tungnaarkrokur and Hrauneyjafoss Project area is presented in a Report by Sigurdur Thoroddsen [1] on his engineering appraisal of several potential projects.

Geologic reconnaissance of remaining areas of the two Basins has not been reported on previously insofar as hydroelectric power development is concerned. No detailed geologic mapping has been accomplished at any of the proposed Project sites.

Subsurface explorations by drilling has amounted to 9 holes in the Tungnaarkrokur reservoir area and 6 holes at a proposed damsite across the Thorisos River near Thorisvatn. The total length of holes is about 500 meters.

Sampling and testing of sources of natural construction materials has been started, but has been limited to the Tungnaa and Thorisvatn areas.

Planning.

Appraisal studies of several of the proposed major sites for hydro-electric power development have been made by Sigurdur Thoroddsen, consulting engineer, Reykjavik, and are presented in his Report to the SEA dated August, 1959(1), and shown on a number of separate drawings which were made available to us. Thoroddsen's work was of important help to us during our reconnaissance and subsequent studies inasmuch as it gave us a well-prepared introduction to the potential of several of the various Project sites.

The Projects discussed in Thoroddsen's Report include Hvitarvatn, Blafell, Gullfoss, Dynjandi and Selfoss in the Hvita River System and Bjallar, Tungnaarkrokur, Hrauneyjafoss, Thorisvatn, Sultartangi, Fossa, and Urridafoss in the Thjorsa Basin.

Other engineering studies have not, to our knowledge, been made during the last 20 years of the potential of the two Rivers and their tributaries.

PRESENT DEVELOPMENT

Development of the hydroelectric resources of southwestern Iceland started in 1935 with the construction of the first power plant on the Sog River, a short tributary to the Hvita originating from Lake Thingvallavatn. The upper section of the Sog drops 76 meters in less than 10 kilometers and this head is now fully developed by the recent completion of Efra-Sog, the last of three power plants. These plants will have a total installation of 96,000 kilowatts, ultimately. This ultimate capacity will require the utilization of some storage in Thingvallavatn to regulate the average flow of about 110 kl/s in this section of the River.

The Efra-Sog power plant utilizes 22 meters of head from Thingvallavatn to a smaller lake, Ulfljotsvatn, which is also the headwater of the second plant, Ljosafoss. A short headrace tunnel at Efra-Sog conveys the water to a surface powerhouse which ultimately will have an installed capacity of 27,000 kilowatts. The initial stage of Ljosafoss was completed in 1937 with an installation of two units, each of 4,400 kilowatts. A third unit of 5,500 kilowatts was added in 1943 and further extensions will increase the capacity of the 17-meter head development to somewhat more than 20,000 kilowatts. The two downstream falls, Irafoss and Kistufoss, were developed in 1953 by a single powerstation located underground near the dam at Irafoss and a 600-meter long tailrace tunnel which returns the water to the river downstream of Kistufoss. The gross head is 38 meters and the present and ultimate capacities are 31,000 and 46,500 kilowatts, respectively.

The power from the Sog Projects is transmitted to the Reykjavik load center, a distance of 50 kilometers, by a 132-kilovolt overhead line which has a carrying capacity equal to the ultimate capability of the Sog Development.

The operation of the Sog Power System is by the Sog Hydro-Electric Power Company which is controlled jointly by the State and by the City of Reykjavik. The experience gained during the planning, construction and operation of the Sog Projects will be of great value for future development of hydroelectric power in Iceland.

Thermal power on the order of 15,000 kilowatts is at present available to the South Iceland Power System. A Diesel plant of 10,000-kilowatt capacity located near Reykjavik, is now used mainly as standby. There is some production by smaller plants in remote areas not yet connected to the main System.

Plans are nearing completion for the construction of a geothermal powerplant of about 15,000-kilowatt capacity located near Reykjavik. This Project is the first attempt to utilize the geothermal resources of Iceland for power, and is planned on an experimental basis.

CHAPTER III

GENERAL DESCRIPTION OF THE HVITA AND THJORSA RIVER BASINS

GENERAL

The Hvita and the Thjorsa River Basins comprise an area of nearly 14,000 square kilometers in the southwestern part of Iceland. The two Rivers originate from the glaciers, Langjokull, Hofsjokull and Vatna-jokull in the central highlands, then flow in nearly parallel courses in a southwesterly direction, discharging into the North Atlantic Ocean about 50 kilometers east of the capital city, Reykjavik. A general plan of the Basins is shown on Exhibit 3. The two Rivers are about 40 kilometers apart in the upper mountainous reaches with the Hvita to the west, but converge to within 4 kilometers on the lava plains south of Hestvatn. The Rivers again separate and are about 25 kilometers apart at their mouths. The principal tributaries of the Hvita River include the Sog, Bruara, Tungufljot, Stora-Laxa, Sanda, and the Jokulfall, while those of the Thjorsa include the Fossa, Tungnaa, and Dalsa. The Kaldakvisl is an important tributary of the Tungnaa.

For the most part the two River Basins are undeveloped and uninhabited; only at the lower altitudes of the plains are there scattered farms and villages connected with a network of gravel roads. Some of these farms are a thousand years old, dating back to the ninth and tenth century, when Iceland was first populated. The countryside is generally barren, without trees, but with grasslands near the coastal section. The Hvita River is bridged at three points, Selfoss, Skalholt and Tungufell, about 15, 60, and 85 kilometers from the mouth, respectively, while the Thjorsa has only one bridge, near Urridafoss, about 20 kilometers from the ocean.

The total population of the Basins is only a few thousand and there is no industry of significance; Reykjavik and environs, with a growing population of about 100,000, is within relatively short transmission distance of most potential power projects.

The Power System in Southwest Iceland may eventually be connected by a 200-kilometer long transmission line to the towns and villages on the north coast. Most of Iceland is rather sparsely populated, as indicated by the fact that less than 200,000 people live on a total area of 100,000 square kilometers.

GEOLOGY

General.

Our understanding of the geology of the Thjorsa and Hvita Basins is based on published and unpublished reports by Gudmundur Kjartansson, Sigurdur Thorarinsson, and Sigurdur Thoroddsen, on field and office discussions with these gentlemen and on our own reconnaissance which covered much of the two Basins. General geologic background relationships that bear directly on the engineering geology related to hydroelectric development within the Hvita and Thjorsa River Basins are reviewed briefly in this Chapter. The geology of specific proposed projects is discussed individually thereto in succeeding Chapters.

All exposed rocks within the two Basins, and for that matter in Iceland, are of volcanic origin, and all superficial materials are derived therefrom or erupted by volcanoes. The older rocks date from the Tertiary Period. Pleistocene and post-glacial glaciation and volcanism are of major importance with respect to the engineering geology, while folding and faulting is only of secondary importance. The bedrock formations hereinafter referred to and discussed follow designations established by Kjartansson and are more fully described in his Report.[2]

The Hvita, the Upper Thjorsa, the Kaldakvisl, and the Upper Tungnaa flow southwestward in parallel courses which correspond with the tectonic grain of south-central Iceland, and also in most places with the direction of ice movement at the climax of the last glacial stage. The northwestward trending segment of the Tungnaa, and similar departures of the courses of the lower Hvita and Thjorsa from the southwest trend, represent diversions of these Rivers by post-glacial lava flows.

The Basins of the Hvita and the Upper Thjorsa are underlain chiefly by a sequence of basalt flows and interbedded sediments, the Grey Basalt and Hreppar Formations, which may be Pliocene to early Pleistocene in age. The topography of both valleys is streamlined in the southwesterly direction by glacial erosion and deposition, and the dam sites are morainal (e.g. at Hvitarvatn) or are associated with waterfalls or rapids which mark the beginning of post-glacial downcutting of the river (e.g. at Gullfoss).

With no sharp boundary this terrain changes to the southeast, between the Thjorsa and the Kaldakvisl, into a glaciated but less severely streamlined topography underlain by the Palagonite Formation, that is, in Icelandic usage, the complex of volcanic materials formed by eruptions which occurred under Pleistocene ice sheets. The topography of the Palagonite belt was largely built up by the subglacial eruptions, and it is from place to place to a greater or less extent shaped by ice erosion depending on whether the volcanism occurred early or late during the period of glaciation. The topographic trend is southwesterly chiefly because discontinuous ridges of Palgonite were formed by eruptions from fissures which parallel the tectonic grain. The course of the Kaldakvisl conforms with this trend, and Lake Thorisvatn occupies an irregularly shaped basin in Palagonite materials and moraine, closed in part by post-glacial lava flows from the east.

Southeast of Thorisvatn the glacially-modified Palagonite topography is largely buried by volcanic features clearly formed after the recession of the last ice sheet. The upper, southwestward-flowing segment of the Tungnaa is bordered in part by volcanoes and craters aligned along the regional tectonic grain, and some of the dam sites on this segment of the River have cinder cones on one or both abutments.

The lower courses of the Tungnaa, the Thjorsa, and the Hvita are in most places located at the margins of the Thjorsa lavas, a sequence of basalt flows about 8000 years old which originated in the area of recent volcanism southeast of Thorisvatn and spread southwestward to the sea. The flows destroyed pre-existing drainage lines in the areas covered; The river segments which border the lava plain are incised across partly buried hills and ridges consisting of the Palagonite, Hreppar, and Grey

Basalt Formations. While there is much variety in detail, all of the local steepenings in profile which favor hydroelectric developments on these river segments are due directly to derangement of the drainage by the Thjorsa lava flows.

Generalizations regarding the engineering-geology properties of each of the major rock units mentioned above, and of several kinds of superficial materials derived from them, are outlined hereinafter.

Grey Basalt Formation.

As seen in the Hvita Valley near Hestvatn, at Gullfoss, at the dam sites near Blafell, and at many places between, the Grey Basalt consists of flows ranging from a few meters to a few tens of meters in thickness, interlayered with sedimentary units of various types with about the same range in thickness. The fact that individual flows and the sedimentary interbeds tend to maintain the same thickness and lithologic characteristics in gorge walls for distances measured in kilometers implies that detailed geologic mapping of the outcropping units, combined with a small number of widely spaced drill holes to determine their altitude in critical places under the valley sides, should make it possible to predict the underground arrangement of the rock units in the vicinity of dam sites and along tunnel alignments.

Most of the Grey Basalt flows show the three zones that are typical of basalt flows generally: (1) a lower zone consisting of large columns oriented normal to the base, the colonnade; (2) a zone of small, irregularly oriented columns and blocky-breaking lava, the entablature; and (3) an upper zone consisting of scoriaceous lava, usually with no systematic joint pattern - this zone may include, at the top, gaping fissures in pressure ridges or a layer of broken slabs and blocks with interconnecting open spaces. There is no general rule as to the ratio of the thickness of any of these zones to the overall thickness of a flow, but they tend to maintain the same characteristics and relative thickness in a given flow in a given area.

While there may be some movement of water laterally through the joints of the colonnade and the entablature, no troublesome water flows are to be anticipated in these zones in tunneling operations. They normally accept little or no grout and need no treatment to assure water tightness. Substantially all of the lateral movement of water in a sequence of flows of the Grey Basalt type is through the fissured and brecciated lava at the contacts and through layers of interbedded sediments if these are permeable.

The differences in arrangement and spacing of joints in the colonnade and the entablature mean that one of these zones is apt to be somewhat more favorable for tunneling than the other; for example, there is apt to be more overbreak in the large columns of the colonnade than in the closely jointed entablature. The tunneling characteristics of the zones, however, depend largely on the orientation of the columns relative to the faces to be cut and on other habits of jointing, as for example the platy parting normal to the columns which is very strongly developed in most of the flows of the Grey Basalt sequence. While these matters need to be considered in the design of excavations, it will usually be impracticable to plan the alignment and level of a tunnel or the position of an underground powerhouse or surge tank so as to keep it entirely in the colonnade or the entablature of a given flow. Both are excellent tunneling rock. It is obviously necessary to avoid interflow contacts insofar as possible or, alternatively, to make advance provisions for handling the heavy flows of water that may be encountered in the contact zones, and for providing temporary or permanent lining that may be required in these zones.

In some places, because of rising of large amounts of steam through the consolidating flow from wet places beneath, the systematic zonal arrangement may give way to "pipes" as much as 25 meters across, characterized by disorderly jointing and breccia or a pillow-palagonite complex (see below) which may be structurally weak or very permeable or both. The location of such pipes is not predictable, but the probability of encountering one or more of them in a given tunneling operation can usually be evaluated on the basis of their frequency of occurrence in canyon wall exposures in the same vicinity.

Most of the sedimentary units within the Grey Basalt sequence are cross-bedded sand and sandy gravel clearly deposited by streams, and finer-grained materials formed in shallow lakes. Some layers consist of angular to subangular stones showing no stratification or size sorting, in a dense and strongly indurated matrix, the combination suggesting deposition at the base of a glacier; but in many places these till-like deposits grade laterally into sediments with bedding and cross-bedding, open spaces between grains, and other characteristic features of the deposits of mudflows and muddy-water streams. The question of origin is significant because sub-glacial till is apt to be consistently tight, while all of the many kinds of mud flows and river deposits may be expected to contain open-work gravel lenses, that is, gravel with no fine grained interstitial material and hence with large interconnecting voids. Most of the till-like deposits seen in the Grey Basalt sequence in the course of our reconnaissance are not till, but this generalization has little meaning except to emphasize the need for care in identifying materials; the origin and engineering properties of individual sedimentary units must be dealt with at the sites where they occur.

Because they are dominantly fine-grained and thoroughly compacted, the sedimentary units in the Grey Basalt Formation are in general very nearly as impermeable as the solid basalt. The overall tightness of the Formation, in contrast, for example, with the Thjorsa lavas, is due chiefly (1) to the presence of fine-grained sedimentary interbeds at nearly all flow contacts, and (2) to the fact that the zone of superficial fissuring and brecciation was removed by erosion from most of the flows prior to deposition of the sedimentary material.

Some of the sedimentary interbeds are sufficiently indurated to form rapids in the bed of the Hvita and overhanging ledges on the gorge walls - there is no question but that these units will stand in the walls and arched roofs of tunnels. It is at least worthy of investigation whether some of the tighter and stronger sedimentary units may be more favorable for tunneling than the basalt.

At and for several kilometers north of the waterfall, Gullfoss, another type of material is interbedded in the Grey Basalt Formation, namely, a sheet of pillow-palagonite breccia. The matrix of the breccia consists chiefly of fragmented glass produced by rapid chilling and explosive shattering of lava entering a lake; the mineraloid palagonite is formed by alteration of the comminuted glass. The brown and yellow colors of the palgonite are caused by weathering to which the mineraloid is very susceptable. Larger elements of the breccia are (1) rounded "pillows" formed by solidification of tongues of molten lava detached from the front of the flow, and (2) angular crusts and slabs carried on the top of the flow and dumped over the front into the lake water. The percentage of matrix, pillows, and crusts vary haphazardly from place to place, and the permeability varies correspondingly from small to very great. There is a similarly haphazard variation from incoherent sand and loose breccia to material with strength nearly equal to that of solid basalt.

The Gullfoss pillow-palagonite breccia is a sheet 10 to 15 meters thick. It shows well-defined foreset bedding which dips 15° to 35° in a southerly direction; the structure is analogous to the foreset bedding in a sand-gravel delta. The Gullfoss sheet is underlain by fine textured sediments deposited on the floor of the lake prior to advance of the pillow-palagonite delta, and is overlain by the solid basalt of the same flow, formed in the dry on top of the delta. In that it is a tabular layer of fairly uniform thickness corresponding with the depth of an ordinary lake, the Gullfoss sheet contrasts sharply with the very much larger and more complex masses of pillow-palagonite breccia, comprising the Palagonite Formation, which was formed by eruptions of basalt into chambers under the Pleistocene ice sheets and is hereinafter discussed.

Because of their extreme and unpredictable variations in permeability and strength, pillow-palagonite sheets of the Gullfoss type should be avoided in tunneling operations insofar as this may be practicable.

Hreppar Formation.

The Hreppar Formation consists of a varied assemblage of rock types including (1) normal basalt flows, (2) sedimentary units of several kinds including probable tillite; (3) palagonite tuff, (4) intrusive and perhaps also extrusive bodies of rhyolite, and (5) sills, dikes, and irregularly shaped masses of basalt intrusive into all of the other rocks. Most of the Hreppar rocks are tight and sound, but the assemblage differs so much from place to place that no significant generalizations can be made regarding its engineering properties.

Palagonite Formation.

As indicated earlier, the Palagonite Formation is defined on the basis of a manner of origin the Formation includes the chaotic assemblage of materials formed by eruptions of magma into chambers melted into or entirely through the Pleistocene ice sheets. It is made up chiefly of a palagonite tuff which may contain pillows, breccia blocks and intrusive bodies in all proportions. From an engineering point of view the best phase of the Formation is palagonite tuff-breccia consisting of angular basalt fragments a few centimeters in diameter in a dense, firmly-indurated matrix of palagonite tuff; material of this type is typically exposed in Vatnafell south of Thorisvatn. The worst phases are open-work breccias and pillow complexes with a matrix of loose palagonite sand, seen in some places in the Tungnaa gorges.

Kjartansson makes the important point that areas underlain by the Palagonite Formation are practically devoid of surface streams, the implication being that it is as a rule highly permeable. An equally significant generalization is that the Palagonite is so complexly structured that it is in most places impossible to infer closely what is beneath the surface on the basis of observations at the surface. It will probably require considerable grouting in dam abutments. Long tunnels or power-station excavations in Palagonite below the watertable, particularly below the level of nearby rivers, should be avoided insofar as possible or explored thoroughly before the beginning of construction.

Thjorsa Lavas.

The post-glacial Thjorsa lava flows disrupted earlier drainage lines throughout the lower courses of the Tungnaa, Thjorsa and Hvita Rivers, forcing these Rivers into new positions at the margins of the lava plain. Most of the hydroelectric dam sites on these Rivers in south-central Iceland are at falls or rapids where the displaced Rivers are cutting downward rapidly across spurs or isolated hills of the pre-lava topography. The potential reservoir basins upstream from some of the dam sites are wide depressions formed by damming of pre-existing valleys by the lava flows; the fact that these basins were originally occupied by lakes is significant both with regard to the tightness of the reservoirs and the availability of silt and clay for use as core and blanket material. Most of the lakes have been filled with sediment and/or drained by down-cutting of the outlet by thru-flowing lava-marginal rivers, such as the basins above the Tungnaarkrokur and Hrauneyjafoss Sites on the Tungnaa.

Others were drained by large rivers which entered the lakes from adjoining uplands, such as the basins of the upper Rauda, of the Fossa above its junctions with the Thjorsa, and of the Thjorsa above the Tungnaa junction. Lake Hestvatn was impounded by the same Thjorsa lava, but it has escaped destruction because neither the Hvita nor any large tributary flows thru it. If the lava had extended only a few meters higher on the east side of Hestfjall, the Hvita would have been diverted around it, and Hestvatn would have been as short-lived as the other lava-marginal lakes. Lake Thorisvatn is similar in all essential respects in that it was impounded by the young lava and has survived because there is no thru-flowing river.

Where the soil cover has been removed by erosion the surface of the youngest of the Thjorsa flows is commonly a maze of pressure ridges with gaping fissures, and the low places between the pressure ridges are occupied by openwork breccia consisting of blocks and crusts of lava. Exposure of interflow contacts in canyon walls indicate that the earlier Thjorsa flows had surfaces similar to that of the last flow. The high degree of permeability of the interflow contacts is indicated by large springs that issue from them at many places, absence of surface drainage lines on the lava plain, and flatness of the watertable where data is available. As indicated earlier, the contrast in permeability between the Thjorsa flows and the Grey Basalt is due largely to the circumstance that surficial fissured and breccia-mantled parts of the Grey Basalt flows were mostly removed by erosion and replaced by tight sediment prior to the spreading of the next flow, while each Thjorsa flow seems to have poured out over the little modified surface of the next earlier flow, with or without a cover of permeable ash.

Because the Thjorsa flows underlie or make up one abutment of many of the project sites, grouting will be required to keep water losses within acceptable limits wherever the dam will develop even a moderate hydraulic gradient thru the lava. Experience with grouting similar flows at dam sites on the Columbia River in the United States indicates that there is no point in slanting the grout holes so as to intersect the near vertical cooling-contraction joints of the colonnade; these joints, and those of the entablature, will accept very little grout, and need none. Acceptance of grout by the interflow contacts will vary greatly from hole to hole, but it may be assumed for purposes of appraisal cost estimates that construction of a curtain in a single contact will require a row of holes on two-meter centers, with an average take per hole on the order of 200 sacks of cement. Detailed drilling and testing in the planning and design phases may permit a closer evaluation.

Superficial Materials.

Alluvial and lacustrine deposits, glacial till, talus, solifluction materials, and volcanic ash enter into foundation problems at some proposed project sites, and they are important sources of construction materials.

As indicated in the discussion of interbedded sediments within the Grey Basalt Formation, various types of mudflows and the deposits of glacial rivers heavily charged with rock flour are readily mistakable for glacial till. In general, deposits of real till, as at the Hvitarvatn Storage

Site may include openwork gravel beds that are in the highest degree permeable. Both the till and till-like deposits are worth considering for use in cores and blankets, the main difficulty being that these materials are usually so strongly indurated that they may be costly to excavate and may require very heavy equipment and special procedures to place.

It is evident on deductive grounds that these must be every graduation between (1) "true" Palagonite, that is, material formed directly by volcanism in water-and steam-filled chambers in the Pleistocene glaciers, and (2) glacial till consisting of Palagonite materials moved and deposited by ice in a given area after cessation of the subglacial volcanism in that area. Moreover, because the final down-melting of the ice from relief features consisting of Palagonite left steep and unstable slopes in some places, the lower parts of these slopes are covered by an accumulation of open-textured talus and rock slide material. Finally, intense frost-shattering of ledges and frost-induced flowage of water-saturated soil in post-glacial time has tended to smooth out all minor topographic features and to mantle all surfaces with solifluction deposits. The general point is made that these various types of materials are difficult to distinguish; actually, they all grade into each other in origin as well as in appearance. As indicated in discussion of individual Sites, an understanding of the origin of combinations of them may be critically important in analyses of foundation conditions.

There are no eskers or other glaciofluvial deposits, nor post-glacial river terrace deposits, near enough to most Project Sites to serve as sources of concrete aggregate. Sand and gravel from riverbeds and alluvial islands may be satisfactory in quality and quantity at some Sites, but it will probably be necessary at most Sites to manufacture aggregate by crushing sound basalt. Reactivity of the local aggregate with available cement must be investigated at each site.

The mantle of volcanic ash that is widespread in south-central Iceland consists of many separate ash falls which differ markedly in grain size and degree of weathering. It is possible that a blend of some or all of these layers, or a blend of the ash together with added clay, silt, or fine sand may make suitable blanket and core material; this possibility is worth investigating at Sites where there are no other natural materials. The highest and best use of the ash may be as a pozzolanic additive or replacement in concrete.

RIVER TYPES

The types of rivers in Iceland have been discussed by Rist in the SEA Report[(1)]. The three main types, designated glacial, linda and draga, have quite different flow characteristics, depending principally on the source and nature of the water supply.

The most characteristic of these types are the glacial rivers which rise from the permanent ice fields of the large glaciers. These rivers carry large amounts of sediments which give the water a brown color near the origin, becoming lighter farther downstream to attain a milky color when it is mixed with water from other streams. Although only a minor part of the water at the mouth of the Hvita and Thjorsa Rivers comes from the glaciers, the characteristic color is still present and they are generally classified as glacial streams.

The flow of a glacial river varies greatly. It increases in June and is high in July and August, then suddenly decreases in September and tends to be very low all through the winter. Daily fluctuations are also significant during the summer. The annual runoff is usually large compared with the drainage area.

Glacial flood bursts are a phenomenon which is probably unique to Iceland. These are violent outbursts of water at the margin of a glacier, and may reach a magnitude of several tens of thousands of cubic meters per second. However, a study by Rist shows that apparently no bursts appreciably greater than normal floods have taken place in the Hvita and Thjorsa River Systems during the past 1000 years.

Linda (spring-fed) rivers represent another characterictic type in Iceland. These have a definite origin, often gushing springs, in which case the discharge reaches full volume not far from the source. These linda rivers are found in the permeable rock formations. The water is clear, since very little sediment is carried, and has a nearly constant temperature of 3 to 5 degrees Centigrade; they do not freeze near the head spring even in the most severe frost.

Draga, the third type of river, receives the water from normal surface runoff. These rivers are found in areas of the Hreppar and Grey Basalt Formations and the more watertight areas of the Palagonite rocks. Their discharge is very much dependent upon the precipitation, and the water temperature varies with the air temperature. Ice is formed quickly when the air temperature falls below freezing. The great floods of the draga rivers carry great volumes of sediments, but at other times the water is crystal clear.

CLIMATE

Surrounded by the North Atlantic Ocean, Iceland has a maritime climate with cool summers and much milder winters than could be expected from its location near the polar circle. The reason for this condition is partly because the waters around Iceland are tempered by the warm Gulf Stream and partly because the prevailing wind direction is from the southwest. Iceland is, however, only 300 kilometers from the large ice and snow masses of Greenland and outbursts of cold air therefrom and from the Polar Sea is a normal winter occurrence. The average temperature in Reykjavik is nearly 4.5 degrees Centigrade; the lowest monthly average is minus one-half degree in December and the highest is eleven degrees in July. There is little difference generally between daily high and low temperatures.

The southern part of Iceland receives considerable precipitation, while the north coast has a much drier climate. The 30-year annual average precipitation for Reykjavik is 900 millimeters, while Akureyri in the north has only about one-half of that amount. The precipitation is less in summer than in winter; at Reykjavik the driest month is June with 49 millimeters average while January is the wettest with 103 millimeters. The precipitation on the south coast is even in the winter months mostly in the form of rain. The temperatures are lower at the higher altitudes of the central region, and nearly all winter precipitation above the 500-meter elevation comes as snow which may accumulate to great depth. Heavy rainfall in the spring may therefore cause considerable snowmelt with resultant flooding, especially when the flow capacity of the normal channels is reduced by ice.

Thunderstorms are not of frequent occurrence in Iceland, but winds can be high, possibly more than 50 meters per second (110 miles per hour).

Precipitation records are meager for the Thjorsa and Hvita Basins. Two meterorological stations exist therein; one on the coast at Eyrarbakki, and the other at Haell about 40 kilometers inland near the Thjorsa River at about elevation 100 meters. No meterorological information is available for the central mountainous parts of the country. The 30-year annual precipitation average for Eyrarbakki and Haell is 1123 and 955 millimeters, respectively. The annual precipitation at the higher altitudes is certainly much higher than near the south coast of Iceland. The average annual discharge of the Hvita and Thjorsa Rivers is 60 and 53 liters per second per square kilometer, respectively, which corresponds to annual equivalent runoff amounts of 1900 and 1650 millimeters average for each Basin respectively. These amounts exceed substantially the recorded precipitation average at the two stations. It is improbable that the annual runoff contribution from the receding glaciers exceeds total evaporation, transpiration and other losses, therefore the actual precipitation must be in excess of that which is apparent on the basis of total average annual runoff measurements.

The winter precipitation in the mountains occurs mainly in the form of snow which may accumulate to great depth. This snow melts during the warmer spring and summer months to cause a considerable increase in the streamflow of most rivers. The snowmelt occurs early at the lower altitudes, while on the glaciers the melting of snow and ice will continue throughout the summer until it ceases early in the autumn. These relationships are favorable in that the snowmelt generally does not cause large floods on the rivers of the Thjorsa and Hvita Basins in the spring.

The hydrologic year is counted from September 1st to August 31st of the following year. Water reserves in the form of snow may vary greatly from one year to another and it is therefore proper to estimate annual yields starting at a time when both snowmelt and snow accumulation is low, normally during late August or early September.

FLOODS

In a supplement to the SEA report on the Thjorsa-Hvita hydrology, Sigurdjon Rist has evaluated the magnitude of 100 and 1000 years floods at various locations on the two Rivers. The streamflow records available are of too short duration to give a reliable basis for an estimate of these floods, and Rist has therefore based his evaluation primarily on descriptions, extending over a period of about 1000 years, of the weather and damage due to floods, landslides, glacial bursts, etc.

The largest floods occurring in Iceland are caused by glacial bursts. No records were found in the old descriptions of large bursts in the Thjorsa-Hvita System during the last 1000 years, and Rist concludes that the greatest floods to be expected are of the winter-flood type which are caused by a sudden inflow of warm and humid air masses over Iceland resulting in heavy rainfall and extensive snowmelting. These floods reach their greatest magnitude when the following events occur in the order listed below:

1. The drainage area is made watertight by freezing of the top layer of the ground and all depressions are filled with ice.
2. The ground is covered with deep snow.
3. Heavy rainfall coinciding with warm wind blowing over the drainage area causing extensive snowmelting.

Under the assumption that no glacial burst will occur, Rist arrives at the following evaluation of the 100-and 1000 year-frequency floods:

River	Location	100 years flood-Kl/s	1000 years flood-Kl/s
Hvita	Hvitarvatn	250	500
Hvita	Blafellsholmi	2000	3000
Hvita	Gullfoss	2500	4000
Hvita	Hestfjall	3500	4500
Hvita	Selfoss	3800	4000 *
Thjorsa	Nordlingaalda	3000	4000
Thjorsa	Dynkur	3500	5000
Thjorsa	Burfell	5000	7000
Thjorsa	Urridafoss	5000	8000
Tungnaa	Tungnaarkrokur	2000	4000
Tungnaa	Confluence with Kaldakvisl	3000	5000
Kaldakvisl plus Thorisos	At confluence	700	1500

* Flooding of land.

GROUNDWATER

Some of the younger Palagonite and lave formations are highly permeable so that the surface water is easily absorbed. This water will then travel through subterranean channels, in many cases for tens of kilometers, and eventually reappear at downstream locations. These permeable rocks are found in the Hvita-Thjorsa River Basins in an area south of Langjokull, in the Palagonite area south and east of Thorisvatn and in the Thjorsa lava plains which include large areas east and south of the Thjorsa River, and east of Thorisvatn. These areas are dry even during sustained rainfall, and the watertable is probably tens of meters below the surface except near rivers or lakes. Surface water is also occasionally forced underground by landslides which have dammed valleys. Rivers which originate from the springs have a very uniform flow generally throughout the year, unaffected by the changes in the weather. The temperature remains constant at about 3 to 5 degrees Centigrade.

SEDIMENTS

Some of the rivers of the Basins carry suspended and bedload in substantial quantities. The glacial rivers carry large quantities consisting mainly of materials eroded from the beds of the rivers and the glaciers. The amount transported is small during low discharges but increases rapidly with the flow. The draga rivers may also carry a substantial volume of sediments resulting from erosion by the river itself and by the surface runoff. The variation and the quantities of their bedload may be proportionately somewhat less than for the glacial streams, however, the variation of sediment with discharge has a similar relationship. The linda rivers usually carry very little sediment, only small amounts of windblown sand and pumice, especially during rare volcanic activity in the neighborhood of such rivers.

The SEA has carried out measurements of suspended sediment load in the Thjorsa and Hvita rivers, the results of which are given in their Report (9). Although these sediment samples have been taken in places of high water velocity and great turbulence, the transportation of a substantial part of the bedload is likely to have escaped measurement. Special samplers have been developed for measuring bedload movement, and the more common types and their use are discussed in Reference No. 10 of the Bibliography.

Ice Conditions

Ice Conditions prevailing in the winter months in the Thjorsa and Hvita River Basins will have an important bearing on the design, construction and operation of hydroelectric projects. The existing conditions thereon are described in the SEA Report [9]. Climatic factors as they relate to ice formation on rivers are no more severe than many places in Europe and North America where hydroelectric plants are in operation. Ice problems in Iceland are, however, complicated by the fact that ice formations in the three stream types, described in Chapter III, above, differ considerably one from another. Frazil and anchor ice is formed in the upper reaches of the glacial and the draga rivers during the early part of the cold weather season before the cooling of the water is prevented by a protecting ice cover. The ice is carried downstream and may increase or decrease in quantity depending on the weather and the amount of warmer water entering from tributary streams containing water from springs. The water from springs has a temperature several degrees above freezing throughout the cold weather season. Rivers fed in whole or in major part by springwater will maintain an open channel near the center for many kilometers even during periods of hard frost. Conditions are favorable for frazil and anchor ice formations especially when the water surface is roughened by frequent high winds or by passing over rapids. The winds also blow snow into the open water which tends to increase the amounts of sludge ice.

Ice jams will develop whenever the moving sludge ice encounters an obstruction such as a surface ice cover or a shallow and irregular stream-bed. The jams may build up to great height in constricted reaches such as the Urridafoss Gorge, but they are usually short-lived. Serious flooding under existing natural conditions does not appear to present a serious problem. Floating sheet ice does not appear to be a major contributor to ice jams under natural conditions.

Specific ice conditions as they may affect hydroelectric development of the two Basins are summarized from the SEA Report:

<u>Thjorsa River:</u> Large amounts of subsurface ice are transported by this River and any initial project must be carefully planned to keep interruptions of operation to a minimum. The construction of any storage or power developments on the Thjorsa or its main tributaries, the Tungnaa and the Kaldakvisl, will tend generally to decrease ice problems at downstream plants.

<u>Tungnaa River:</u> Some ice problems may be expected, but the quantity of ice would be much less than in the Thjorsa. Powerplants must have facilities to handle frazil and anchor ice.

<u>Thorisvatn Storage and Kaldakvisl Diversion.</u> No ice problems are expected with the intake located in the Lake.

<u>Hvita River.</u> No serious ice problems are expected in the upper reaches. At Gullfoss and Hestvatn it may be essential to design the reservoirs (and canals) so as to permit an ice cover to be formed during the coldest months.

CHAPTER IV

HVITA RIVER DEVELOPMENT

GENERAL

The Hvita River originates from Lake Hvitarvatn, located in a depression east of the Langjokull ice cap, and flows for 130 kilometers in a southwesterly direction until it reaches the North Atlantic Ocean at Eyrarbakki. The section downstream of the confluence with the tributary, Sog, about 25 kilometers from the sea, is called the Olfusa River. The Sog River, which drains Iceland's largest lake, Thingvallavatn, has been nearly fully developed for hydroelectric power. A number of other rivers join the Hvita to form a total drainage area of 6100 square kilometers. The tributaries entering from the east include the Jokulfall, Sanda, Budara, and Stora-Laxa Rivers, listed in increasing distance from Hvitarvatn; the Tungufljot and Bruara Rivers join the Hvita from the west. The location of these Rivers is shown in plan on Exhibit 3.

The total fall of the Hvita River is 421 meters, as shown on the profile of Exhibit 4, of which more than 300 meters are concentrated in the upper 45 kilometers, mainly at the two Blafell and Gullfoss reaches. Blafell is a mountain just south of Hvitarvatn and the Hvita falls 160 meters as it flows in a hemicycle for 25 kilometers around it to the east and south. The waterfall, Gullfoss, with a drop of 30 meters into a narrow inner gorge, is one of Iceland's main tourist attractions and is located 95 kilometers from the mouth of the River. Including rapids immediately upstream and downstream of Gullfoss, the total fall is about 120 meters in nine kilometers. The river gradient becomes progressively flatter downstream of the rapids, and the total drop from near the farm, Haukholt, located twelve kilometers south of Gullfoss, to the vicinity of the mountain, Hestfjall, is only 25 meters in a reach of nearly 40 kilometers. As the River flows for ten kilometers around Hestfjall, it falls from elevation 50 to elevation 33 meters; then resumes a gentle slope until it reaches Selfoss, about 25 kilometers farther downstream. Selfoss represents the last falls on the Hvita (Olfusa) before it reaches the low gradient of the coastal plains. About seven meters of drop are concentrated in 800 meters of rapids as the River drops from elevation 14 meters. The only high-gradient tributary rivers of significance are Stora-Laxa and Tungufljot. The former has its source at elevation about 700 meters in the mountain range between the Thjorsa and Hvita Rivers; Tungufljot originates from Lake Sandvatn at about elevation 270 meters and drops more than 200 meters in less than 30 kilometers.

STREAMFLOW

Differences in precipitation and runoff conditions throughout the Hvita Basin result in great variations in the streamflow pattern and characteristics. In the uppermost reach at Blafell, the Hvita is primarily a glacial river with great fluctuation in flow from summer to winter. This characteristic has been somewhat modified at Gullfoss by considerable inflow of surface runoff water. The linda rivers entering the Hvita downstream of Gullfoss tend to reduce the variations in flow even further.

Streamflow data and studies made by the SEA[9] for the eight-year period 1950-51 to 1957-58, show clearly the flow variation relationships. At Aboti, five kilometers downstream of Hvitarvatn, the lowest and the highest monthly average was 32 and 650 percent, respectively, of the eight-year average. At Gullfoss these same percentages are 32 and 325 percent; at Hestfjall 60 and 270 percent, and at Selfoss 67 and 220 percent. The Hvita-Olfusa River is the largest in Iceland on the basis of average flow. The average discharge at Selfoss is estimated at 386 kl/s as compared to 377 kl/s for the Thjorsa River at Urridafoss. The Jokulsa a Fjollum in the more arid northern part of Iceland has a larger drainage area but considerably less average flow than either the Hvita or the Thjorsa.

The Hvita tributaries are not large rivers. The following table gives the drainage area and estimated average flow of the main tributaries listed in sequence proceeding upstream:

Data for Hvita River Tributaries

River	Drainage Area Square Kilometers	Average Flow kl/s
Sog	1200	120
Bruara	707	67
Stora-Laxa	512	30
Tungufljot	770	50
Sanda	327	18
Jokulfall	380	23

The Sog River, which has been nearly fully developed, is outside the scope of this Report. The Bruara and Tungufljot are both partly spring-fed and maintain a fairly uniform flow throughout the year. The other tributaries listed above are primarily glacial or draga types with relatively great seasonal variations in flow. The remainder of the Basin upstream from Selfoss and exclusive of the 843 square kilometers tributary to Hvitarvatn, includes about 1,000 square kilometers drained by smaller streams. The discharge of Hvitarvatn is estimated to average 53 kl/s.

POTENTIAL POWER DEVELOPMENT

The possible storage and power development of the Hvita River is discussed by individual Project in Chapters V, VI, VII, VIII, and XVIII. The location of potential Projects is shown in plan on Exhibit 3 and in profile on Exhibit 4. However, the general arrangement of each Project (or group of several Projects) as shown on the two Exhibits is intended to be illustrative only, and is not intended to present our specific recommendations for the development of each. The adopted layout for each can, in general, be established only after much further detailed investigations and studies. The required investigations and alternatives to be studied are suggested or recommended by us in the specific Chapters referred to above. The arrangement shown on the two Exhibits presents our present opinion, based principally on judgment, of what may be near the optimum development for each proposed Project. Pertinent data with respect to each such Project is shown on Exhibit 5.

The power and the energy production of the overall development of the Hvita River, as shown on Exhibits 3 and 4, has been estimated by us. The estimated average annual energy production is about 3100 million kilowatthours. The estimated total ultimate capacity installation would be about 600, 000 kilowatts. Some additional power and energy may possibly be developed economically by smaller Projects which we have not investigated. These Projects may be located on tributaries, such as the Stora-Laxa River, or represented by relatively low head developments on the Hvita, which do not appear attractive on the basis of the incomplete information available to us. There is a possibility, discussed in Chapter XVIII of the diversion of a portion of the waters of the Stora-Laxa to the Thjorsa River watershed. Potential Projects which we have studied are outlined hereinafter.

The economics of power development of the Hvita River are dependent to a large degree on the creation of a seasonal storage reservoir at Lake Hvitarvatn. This storage and regulation Project is discussed in Chapter VI. A control dam would be constructed on the Hvita two or three kilometers downstream of the outlet from the Lake to raise the level fourteen meters or more. Seasonal storage amounting to about 800 million cubic meters or more could be created. The waters of the Jokulfall River would be regulated by diversion into Hvitarvatn with a dam located 1.5 kilometers upstream of the mouth of that River. The additional, but variable, head created by the dam on the Hvita may or may not be utilized for power.

There are several alternatives for developing all or part of the head on the Hvita River between Hvitarvatn and Fremstaver, south of Blafell, as discussed in Chapter VII. The total gross head which may be developed economically might range between about 135 and 170 meters. The alternatives range from a single Project to develop nearly all of the head by a long tunnel to a multi-stage plan consisting of three or four individual Projects, each of which would develop head with separate dams and relatively short tunnels or canals. The latter plan may sacrifice some of the total head but will, in major part, utilize for power the substantial intervening inflow, principally from the Sanda River. The multi-stage plan involves smaller Projects, the production of which may be fitted more readily to the pattern of normal load growth. Hence, they may be more readily financable. The proposed Fremstaver Project, located farthest downstream, with a multi-stage development, may be difficult to justify economically. Also there are about ten meters or more of head which we do not now propose to develop between the Fremstaver tailwater and the reservoir for the Gullfoss Project. There may thus be up to about 45 meters of head between the Gullfoss Project and the tailwater of the farthest downstream Project justifiable within the Blafell Reach which cannot be developed economically in the reasonably foreseeable future.

The waterfall, Gullfoss, and contiguous rapids upstream and downstream therefrom represents the second head concentration on the Hvita River downstream from Hvitarvatn and generally favorable for the development of hydroelectric power. The high-gradient reach of the River would be developed in one stage, the Gullfoss Project. A second Project, Haukholt, located immediately downstream in the portion of the River with a gradually decreasing gradient, may possibly be feasible of economic development. The respective heads to be developed by each Project are somewhat interdependent and would be established by the investigations and studies proposed in Chapter VIII. The remaining 27 meters of fall on the Hvita downstream of Haukholt to the mouth of the Bruara River at elevation 50 meters are not now considered feasible of economic development. An alternative Gullfoss Project would divert the waters of the Hvita River through a long tunnel to the Tungufljot, with at-site development of about 147 meters of gross head. About 40 meters of fall might be developed farther downstream on the Tungufljot, as discussed in Chapter XVIII, leaving six meters undeveloped.

The Gullfoss Project, as currently conceived, would include a dam, a tunnel about seven kilometers long, and a powerstation. The dam would be located about four kilometers upstream of the waterfall and would create a reservoir to somewhat above elevation 240 meters with adequate pondage, but without seasonal storage. The tunnel would return the diverted water to the Hvita at Nautavik, four kilometers downstream of the waterfall. The tailwater level would be about 114 meters; thus 126 meters or more of the gross head would be developed. The proposed arrangement favors a low capacity factor powerstation designed for peaking operations ultimately. Preservation of Gullfoss as a scenic attraction may require, at times, the undeveloped release of some water from the reservoir. This loss to power could be offset by diversion of the Tungufljot at Sandvatn through the Sanda River, which joins the Hvita upstream from the Gullfoss Reservoir.

The Haukholt Project, with the Gullfoss Project constructed as outlined above, would include a dam to concentrate about 37 meters of head, and a powerhouse served directly by penstocks from the reservoir.

The Hestvatn Project, described in Chapter V, would develop the 17 meters of fall where the Hvita passes around Hestfjall. Two relatively short canals at each end of Lake Hestvatn would convert that Lake into a water conductor with included pondage. A relatively low, gated structure on the Hvita east of Hestfjall would maintain a nearly uniform reservoir level for nearly all flows and prevent the artificial flooding of low-lying, developed grazing land to the east. A surface powerhouse would be located adjacent to the Hvita at a tailwater elevation of 33 meters, and at the downstream end of the outlet canal.

The Selfoss Project would develop about seven meters of fall at the rapids and waterfall of that same name. This Project would consist of a single continuous structure including a gated spillway and surface powerhouse with integral intake, as described in Chapter XVIII. The cost of reservoir adjustments in the town of Selfoss may be substantial. The Selfoss Project is, for economic reasons, the only one proposed within the lowest 25 kilometers of the Hvita (Olfusa) River wherein there is a total fall of 33 meters. Units energy costs at the Selfoss Project, which would be an energy plant principally, may, however, be relatively high.

There is the possibility, discussed in Chapter X, of diverting the Hvita River from near Hestfjall to the Thjorsa River upstream of Urridafoss. The diversion would eliminate the Hestvatn and Selfoss Projects; the Hvita water would be used through a greater total head at an enlarged Urridafoss Project.

The creation of a seasonal storage and reregulation reservoir at Lake Apavatn, discussed in Chapter XVIII, may be attractive. Up to about 100 million cubic meters of storage may be created, principally by drawdown below normal lake levels. The dam for the Dynjandi Project appears to be the logical control structure. The development of about ten meters of fall above elevation 50 meters, the approximate backwater level for the Hestvatn Project, for power is discussed in Chapter XVIII. The relatively small Dynjandi Powerplant could be remotely controlled from the Hestvatn Project.

About 40 meters of gross head in about twelve kilometers on the Tungufljot River could be developed for power by the proposed Vatnsleysufoss Project. About six meters of fall between the tailwater thereof and the Hestvatn Reservoir level would remain undeveloped. The Vatnsleysufoss Project, as presented in Chapter XVIII, would consist of a diversion dam located about 4 kilometers upstream of the Fossvad Bridge, an underground powerstation remotely controlled from another Project, probably Hestvatn, and a 4.5 kilometer tailtunnel. No seasonal storage would be created, but adequate pondage would be available. The water available for power at Vatnsleysufoss would be greatly dependent on the two diversions, either or both, discussed above for the Gullfoss Project.

The development of the remaining head for power of about 175 meters on the Tungufljot in the 18 kilometers between the Vatnsleysufoss Reservoir and Sandvatn has not been studied in detail. The relatively small Project or Projects which may be potential therein would be somewhat subject to the proposed diversion to the Hvita at Sandvatn. Power development of the other tributaries of the Hvita River also has not been studied in detail. Any feasible potential Projects would individually have a relatively small power and energy capability. None of the tributaries appear to present any appreciable seasonal storage potential.

The geologic setting of each of the proposed Projects to develop the Hvita River for hydraulic power and energy is, in general, favorable. No serious or unusual subsurface problems are believed to exist, with the possible exception of the long tunnel routes of some of the alternatives for the development of the Blafell Reach. Deposits of natural construction materials for each Project are believed to be adequate as to quantity, quality, and reasonable haul distance. Individual designs must, of course, reflect the availability and suitability of these materials.

CHAPTER V

HESTVATN PROJECT

GENERAL TOPOGRAPHY AND GEOLOGY

The Hestvatn Project would develop about 17 meters of fall where the Thjorsa lavas have forced the Hvita River to flow in a relatively narrow gorge along the east and south sides of the mountain, Hestfjall. The deep natural lake, Hestvatn, located on the northwest side of Hestfjall provides a nearly complete headrace across this bend. The lake drains easterly through a low gradient outlet channel about one kilometer long to the main River; and the direction of this flow is reversed during flood stages on the Hvita. A low Palagonite saddle separates the southwest end of the lake from the River downstream from the bend. The Hvita River is relatively wide and of low gradient upstream and downstream from the Hestfjall bend.

The Thjorsa lavas form a low, level, grass-covered plain northeast from Hestfjall to Vordufell and between the Hvita and Thjorsa Rivers which are here only about six kilometers apart. Inasmuch as this plain is only a few meters above normal levels in the two Rivers, extreme floods result in a joining of the Rivers and flooding of the plain.

Topography of the general area of the Project is available on scales of 1:50,000 and 1:100,000. A hydrographic map of the Lake on a scale of 1:5,000 is also available. Some soundings, probings and general surface elevations in the vicinity of the outlet channel from Hestvatn were obtained recently by SEA and added to the hydrographic map. Detailed topography and some probings were also recently obtained by the SEA and plotted on a scale of 1:2,000 along the low saddle between the southwest end of Hestvatn and the Hvita.

The general vicinity of the Project is a developed agricultural area and is well served with a network of main highways and farm roads.

DEVELOPMENT ALTERNATIVES

The plan of development for the Hestvatn Project is so clearly indicated by topographic and geologic relationships as to not require studies of general alternatives. The plan will require principally:

1. A spillway weir on the Hvita east of Hestfjall
2. A diversion canal between the Hvita and Hestvatn and near the existing outlet channel
3. A headrace canal extending from the southwest end of the Lake through the low saddle to the powerhouse, and
4. A powerhouse and appurtenances located on the right bank of the Hvita near the mouth of the Hlaupandi. This plan of development is shown on Exhibit 6.

Details of each of these four main elements would be determined by specific alternative design analyses. Transmission facilities extending to Reykjavik would also be required and would be designed in consideration of existing and proposed future developments.

SPILLWAY AND RESERVOIR

The spillway would be located in the general vicinity shown on Exhibit 6. Our field reconnaissance indicated generally uniform conditions in the River for a distance of about one kilometer upstream from the first small rapids, and a specific location within this favorable reach will require detailed surveys and borings. The River in this reach appeared to be flowing mainly on Thjorsa lava with a narrow and somewhat deeper channel developed on the lava-Palagonite contact near the right (west) bank. The right abutment would be located in apparently good Palagonite requiring little or no grouting. The main weir would be founded principally on good quality Thjorsa lava. A grout curtain would be required and would extend through the underlying contact. The left abutment would be of Thjorsa lava also, and extension of the grout curtain eastward and beyond the end of the structures for a distance of 100 or 200 meters to reduce short-path leakage would be required.

The required manner of operation of the reservoir on the Hvita will control the design of the spillway structure. This operation will be on the basis of an established "rule curve" and will be such as not to increase existing flooding hazards on the adjacent plain between the Hvita and the Thjorsa or affect seriously, for all lesser flow conditions, groundwater levels or drainage problems within that plain. In this regard, a dike extending from the spillway structure and upstream along the left bank to Vordufell is not considered economically practicable as a means of increasing head on the Hestvatn powerplant, though it might have some flood control value. The reservoir would be retained within the existing river channel and to the maximum levels which would still fulfill the above requirements. This means that there will be a "control" point on the Hvita, probably in the vicinity of the diversion canal to Hestvatn, which would serve as the operating guide for the Project. Releases through the powerplant and spillway would be controlled so as not to exceed established rule curve levels and at the same time maintain maximum power head until the possible damages referred to above would occur naturally. Under the latter condition the spillway gates would be fully open. The rule curve of operation can, for design purposes, be established by reservoir backwater studies computed from hydraulic data which it will be necessary to obtain. These studies will also establish the approximate location for the control point. It will be necessary as a part of the Project construction to include a continuous stage recording station at the selected control point with direct transmission of stages to the powerhouse control room by telemark or similar method. Modification of the operating rule curve based on observations from actual operation subsequent to construction may be required but should be of only minor nature.

On the basis of our present information, it seems probable that the minimum elevation of the reservoir at the control point may be elevation 50 meters or slightly higher. We do not now believe that permanently retaining the reservoir to such elevation will produce any appreciable long-path leakage loss through the lava under the plain located to the east.

The principal hydraulic requirement in the design of the spillway structure in order to fulfill the above reservoir requirements is the maintenance of hydraulic efficiency substantially equal to that of the reach of the natural river which the structure replaces. Critical flow conditions through the structure during high-flow, fully-open conditions must be prohibited. To accomplish this it will be necessary to maintain a clear opening in the spillway which is approximately equal to the natural river cross section and for nearly the full range of flows. There should be no backwater effect upstream from the spillway with the gates fully open at any discharge, and with discharge through the powerhouse. This feature should be checked by a hydraulic model study and it will be necessary to obtain adequate topographic, hydrographic and hydraulic data to construct and calibrate the model. The type of energy dissipation required at the spillway for partial and fully-open gate operation should also be verified in the model.

The spillway structure will, in order to fulfill the above requirement, consist essentially of a low concrete sill with crest at or near present riverbed level and surmounted by piers and gates. The structure will occupy nearly the full width of the existing river channel and would thus be about 180 meters long. Tainter gates with a relatively high width-height ratio (3 to 1 or greater) may be the most economic type from an overall standpoint. One or more such gates designed to recess slightly and pass floating ice and debris over the top, thus saving water, may be desirable. Fish-belly flap-gates may be considered as an alternative to tainter gates. The tainter gates may be operated by either electric-driven or hydraulic-operated hoists, with the latter probably the more reliable and least costly. Their operation should be by remote control from the powerhouse. It may be desirable to install a transmitting type stage recorder at the spillway similar to that at the control point.

The hydraulic studies required for reservoir operation will also establish the top elevation of the spillway gates.

The type of spillway design recommended permits passing a flood of any probable magnitude. The spillway deck should clear the surface of a flood of reasonable magnitude; extreme periods could at most produce only superficial damage.

DIVERSION CANAL

The alignment and dimensions of the diversion canal between the Hvita and Hestvatn will be established by design studies after the reservoir operation rule curve has been determined. At least two alternative alignments should be studied. One would consist of enlarging the existing outlet channel to the required dimensions. Bedrock along this route, on the basis of present information, appears to be below any probable canal grade, but this would need to be verified by additional borings and probings. An alternative alignment is shown on Exhibit 6. This latter alignment would probably involve less total excavation quantities than enlarging the outlet channel. However, recent probings indicate that rock would be encountered for a distance of about 300 meters and the additional removal cost may tend to offset that of probably greater total quantitites along the outlet channel route. This rock is probably part of the Grey Basalt series and would require systematic drilling and blasting for removal. The nature of the overburden material must be investigated in detail in order to establish safe design side-slopes of the canal located therein. All of the excavated material can doubtless be removed by dragline though it may be necessary to construct a working platform of fill where excavation is required out into the river or into the lake.

The available maps indicate some tendency for silt deposition where either of these canal routes joins the Hvita. Detailed studies may show that it will be necessary to construct groins of rock-fill on the left side of the river in order to divert the main current towards the right bank and thus scour out these deposits during floods. Occasional maintenance dredging in this vicinity may also be required.

The design of the dimensions of the canal should consider not only economic cross-section factors but also features of design to overcome possible ice problems. Greater depth and lower velocites than would ordinarily be provided may be desirable and would contribute to a cover of sheet ice. It is likely that sheet ice would cover the reservoir under most winter conditions downstream from the diversion canal entrance as far as the spillway. Hestvatn would be similarly covered. Insofar as feasible, an ice cover over the diversion canal under most winter conditions would be desirable. This would tend to prevent sludge ice forming a temporary barrier within or near the downstream end of the canal. It is probable that an open channel will persist upstream from the canal entrance though the higher water levels resulting from the dam may decrease this condition somewhat or even result in a complete ice cover under the most sever winter conditions. Creation of a partial or even complete temporary ice barrier at the canal entrance by sludge ice is not likely to produce a jam extending upstream which would be more than a meter or two in height because of the relatively great width of the reservoir. The resulting tendency for increased water levels can be offset by opening of spillway gates as required; the design of these gates must provide that they be operable under the most severe winter conditions.

The maximum average velocity through the diversion canal which would assure an ice cover thereon during most winter conditions is not exactly determinable. We believe at this time that the design velocity should not be much greater than one meter per second. We suggest a minimum canal depth of about five meters. Inasmuch as the station flow capacity may be increased after upstream regulation is provided, consideration must be given to this ultimate capacity and the design studies must appraise the initial provision of such capacity versus an initial capacity with provision for enlargement.

HEADRACE CANAL

The most economical location for the headrace canal appears to be through the low saddle as indicated on Exhibit 6. An alternative location extending westward into the Hlaupandi appears to be more costly on an overall basis. This latter location would involve the powerhouse and appurtenances blocking that valley near its mouth with the Hvita. An analysis of this alternative plan may be desirable in the planning stage.

The excavation will, on the basis of present information, be almost entirely in Palagonite with little overburden. The quality of this rock along the selected route will need to be checked by drilling. It is our present opinion, however, that steep side-slopes in the excavation will be feasible and that no lining or other major leakage prevention measures will be required.

Most of the design requirements outlined above for the diversion canal will apply also to the headrace canal. Design studies to establish the grade elevation must consider drawdown of Hestvatn for daily and weekly pondage. Maximum average design velocities should provide for ice cover thereon insofar as feasible, and considering that the full flow capacity of the powerhouse would be utilized almost daily. Inasmuch as Hestvatn should have an ice cover much of the time during the winter season, temporary blockage of the canal by sludge ice should not occur. Sludge ice in the canal itself should pass through the units without serious difficulty. The canal should be constructed initially to ultimate capacity for about 100 meters upstream from the powerhouse in order to obviate the need for underwater blasting near the operating units at a future time. The design studies will establish whether or not this ultimate capacity should be provided for the entire length.

POWERHOUSE AND EQUIPMENT

The powerhouse would be of the indoor type with integral intake, and of reinforced concrete construction. A partially underground station of the trench type may be worthy of study as an alternative. The initial construction should include provisions for adding such additional generating units as the design studies may justify. The exact location of the powerhouse with respect to the end of the headrace canal and the end of the railrace in the Hvita will also be established on an economic basis by the design studies. Short wing dams, probably of concrete construction, will be required on one or both ends of the intake to enclose the forebay. Each of these should include an ice sluice.

The foundation rock for the powerhouse and appurtenant structures is expected to be Palagonite of adequate quality. Diamond core drilling and water pressure testing of the foundation rock will be necessary prior to final determination of location of these structures and the design thereof. A grout curtain under the structures and for some distance beyond will almost certainly be required to assure watertightness.

The powerhouse equipment will be essentially conventional. The trashracks must be entirely submerged and equipped for heating. They should be easily removable inasmuch as their complete removal may be desirable during periods of sludge ice. The turbines would be of the automatically adjustable blade propellor (Kaplan) type. However, the design studies should investigate the comparative economics of fixed blade propellor turbines inasmuch as the head is not likely to vary appreciably with variations in river flow. Columnar type stay rings may also be an economic advantage. Provision for heating either the wheel pits or the submerged turbine parts to remove or prevent the build-up of ice thereon should be provided. The ice sluice gates may need to be of special design. All other powerhouse equipment would be essentially standard for projects of this type.

The economic number of generating units would be a subject for detailed design studies. It is probable that they would indicate either two initial units with provision for a third or three initial units with provisions for one or two future units.

WATER SUPPLY, POWER, AND ENERGY

Estimates of discharge of the Hvita River at Hestfjall, near the spillway for the proposed Hestvatn Project, are included in the SEA Report[9]. These flows are tabulated on an average monthly basis and plotted as a continuous hydrograph on an average weekly basis for the eight-year period, September 1950 to August 1958, inclusive. A duration curve based on these flows is also included. The flows were calculated from the daily records of the Sog at Ljosafoss and the Olfusa at Selfoss.

Significant data from these records are as follows:

Average discharge - 8 years	262 kl/s
Average discharge - minimum year	195 kl/s
Minimum monthly discharge	155 kl/s
Minimum weekly discharge	100 kl/s
95% Discharge	150 kl/s
50% Discharge	230 kl/s
34% Discharge	262 kl/s

System Operation studies which would consider the Hestvatn Project as an addition to the then existing system will be required in order to establish the initial and ultimate capacity for the Project. The determination of ultimate capacity would consider regulation by seasonal storage reservoirs such as Hvitarvatn and Apavatn. In view of the relatively low head, Hestvatn initially should probably be considered primarily a base load energy plant operating at a relatively high capacity factor. However, the reservoir including Lake Hestvatn will provide a considerable degree of pondage without any known severe operating restrictions and it may become economic to add considerable peaking capacity ultimately. The design of the initial project should consider this possible eventuality.

We believe that the initial flow capacity of the Hestvatn Project should be about equal to the average annual flow and divided between two units and with initial provision for a future unit of like size. The design layout should permit adding one unit at some future time for an ultimate total of four. The initial capacity would amount to about 35,000 kilowatts. The average gross annual energy production would amount to about 280 million kilowatt hours, which would reduce to about 210 million kilowatt hours in the minimum year of record. These estimated values are based on the flows of record. Corresponding annual capacity factors assuming all energy utilized on load would be about 90 and 70 percent, respectively. It must be recognized, however, that the flow record is somewhat short and may not be truly representative of long-term conditions. Also, drier years than 1950-51 can certainly be expected. Comparison of longer term meteorological and hydrological records with these for the eight years of flow record may give some clue as regards these relationships.

The unregulated run-of-river energy production from the Hestvatn Project may not be fully utilizable to load during initial years of operation. The flows tend to be somewhat minimal during the winter months of colder weather when energy demands are expected to be high. The supply system for Southwest Iceland may become energy deficient at this critical time not long after Hestvatn is completed unless other resources are added. Regulation by a storage reservoir on the Hvita would alleviate such a deficiency. The System Operation Studies may show that such storage can be added economically (in comparison with alternative capacity and energy additions) along with or shortly after the construction of Hestvatn.

FIELD INVESTIGATIONS

Reservoir

The field investigations required for the reservoir will include some topographic mapping. The area between the spillway location and Vordufell should be mapped on a scale of 1:5000 with one-half meter contours. A width of one kilometer from the river should be adequate, but may need to be extended up the small drainages. The field survey should include the locating and setting of elevation reference marks or gages for measurement of the groundwater table away from the River and under the plain. These groundwater measurements may be made at natural depressions or in shallow holes drilled with a percussion drill, and should cover as wide a range of River levels as feasible. Readings on some should be continued into the operating period as long as necessary or desirable.

River cross-sections and associated stage discharge records at intervals of about one or two kilometers will be required from below the spillway location to as far upstream as the mouth of the Bruara. These data will permit the computing of backwater curves basic to establishing a design operating rule curve for the reservoir. They would also supply data for the spillway hydraulic model.

Spillway

A few lines of soundings across the river in the reach proposed generally for the spillway should permit selecting a preliminary alignment. Diamond drill holes and water pressure tests along this alignment will be needed to verify the selection. A minimum of four drill holes in the riverbed section would be required. One or more additional borings at each abutment and beyond the left abutment at the finally selected axis would be required.

Diversion Canal

The principal requirement for additional field information for the diversion canal consists of additional probings to further establish the bedrock surface and thus permit a close evaluation between the possible canal routes. At least one diamond drill hole into any rock to be encountered by the excavation would be desirable. Sampling and testing of the overburden material along the selected route would also be necessary.

Headrace Canal and Powerhouse

Borings and accompanying permeability tests will be required along the headrace canal route and under the selected site of the structures. Tests at 200-meter centers along the canal should be adequate. At least eight borings should be made within the foundation area of the powerhouse and appurtenances.

Existing topography would need to be extended to include the tailrace limits within the bed of the Hvita. A tailwater rating curve will need to be developed.

Geology

There appears to be no requirement for areal geologic mapping of the Project area. Stratigraphic relationship should be developed locally from the boring information and exposures at the site of each principal Project element.

CONSTRUCTION MATERIAL

Concrete aggregate is the only local construction material required. Fine aggregate may be obtainable from bars observed in the bed of the Hvita. Samples should be obtained therefrom and tested. Coarse aggregate can most likely be manufactured from either the Thjorsa lavas or the Grey Basalts. Palagonite from required excavations is not considered suitable.

Gravel deposits were observed in the area north of Hestvatn and are probably associated with an ancient shoreline. Additional field reconnaissance would almost certainly locate adequate deposits suitable for economical processing as coarse aggregates, and might locate similar deposits of fine aggregates. Sampling and testing would, of course, be required at the time of design.

CHAPTER VI

HVITARVATN STORAGE

GENERAL TOPOGRAPHY AND GEOLOGY

Lake Hvitarvatn, the origin of the Hvita River, presents an excellent possibility for development as a seasonal storage reservoir. It receives its inflow largely from the Langjokull icecap located nearby to the west and north. Some surface inflow is contributed by the relatively small Svarta River. Subsurface inflow can only be minor because of the general watertightness of the bedrock and ground moraine which enclose the depression occupied by the Lake. The surface inflow can be increased substantially by diversion of the Jokulfall River which rises near the Hofsjokull icecap to the northeast and flows for about 40 kilometers to enter the Hvita about four kilometers downstream from Hvitarvatn. The drainage area above the outlet of Hvitarvatn is about 840 square kilometers of which about 330 square kilometers is represented by ice fields. The drainage area of the Jokulfall is about 380 square kilometers.

Hvitarvatn is shallow for several kilometers upstream of the outlet and drawdown below the present level is not feasible. Storage would need to be provided by a dam at or near the outlet. The surface area of the natural Lake at its present elevation of about 421 meters is 30 square kilometers and would be only slightly greater if raised ten to twenty meters.

The maximum present depth is about 80 meters towards the north end opposite the large delta, Hvitarnes, which the glacial river, Fulakvisl, is building into the Lake on the east side.

Hvitarvatn is surrounded by mountains or glaciers on all sides other than the east where the land is gently rolling for more than ten kilometers. The mountain, Blafell, dominates the terrain to the south.

The Hvita River flows on almost a flat grade for three kilometers from the Lake to the mouth of the Jokulfall, then steepens slightly for the next two kilometers to the Aboti waterfall where the elevation just upstream is about 412 meters. Aboti is the beginning of a falls and rapids section of the Hvita River which extends downstream for many kilometers.

The geology in the Hvitarvatn area is described by Kjartansson[2]. The bedrock is composed of the Breccia and Grey Basalt Formations. The former dominates the north one-half of the Lake basin, in Blafell and in the hill, Lambafell, which adjoins Blafell on the northeast. The Grey Basalt dominates most of the remaining area. Generally the mountains are of the Breccia Formation and the Grey Basalts occupy the lowlands between.

The bedrock in the general area between the outlet of Hvitarvatn and Aboti is covered by ground moraine, in most places probably to a considerable depth. The moraine forms the low divide between the Hvita and the Jokulfall. It attains a maximum height in the divide of only about 20 meters above the present level of Hvitarvatn. Provision of storage much above elevation 435 would thus require a rather long dam which, however, might be justified.

Recent topography on a scale of 1:10,000 with five-meter contours is available for the area between Hvitarvatn and Aboti and covers adequately for planning purposes the area of any proposed structures. These maps are also available for a much larger area following the Hvita around to the southeast of Blafell. A hydrographic survey of Hvitarvatn on a scale of 1:10,000 is also available. The upper five meters are contoured at one-meter intervals, and the ten-meter contours are shown on the remainder of the Lake bottom. An area-volume curve for raising Hvitarvatn from 420 to 432 meters was prepared by Thoroddsen, and shows a total volume between these levels of 590 million cubic meters.

The general area of the outlet end of Hvitarvatn was covered by our field reconnaissance. The area may be reached by the single-lane road from the south and which has a light gravel surfacing in places. The road crosses the Hvita over a light bridge a short distance downstream from the outlet of the Lake, and continues on to the north. Otherwise, the general area is undeveloped and uninhabitated.

DEVELOPMENT ALTERNATIVES

This presentation of the Hvitarvatn Project is concerned principally with provision for seasonal storage; possible at-site power development is discussed in Chapter VII. Storage will require a dam to raise the Lake level. The dam may contain only the waters of Hvitarvatn, perhaps by an initial low-stage designed for ultimate raising, or it may extend to cross the Jokulfall and divert the waters of that River into the controlled storage.

The development of Hvitarvatn represents the only large storage potential on the Hvita River. The available storage up to elevation 435 meters, estimated to be about 800 million cubic meters, appears to be less than the optimum which might be desired for the Hvita alone. However, positioning the dam in the ultimate development to cross the Jokulfall may be little if any more costly than containing a raised Hvitarvatn alone. The resulting regulation of the flow of that River is certain to be very beneficial regardless of the somewhat limited storage available. The sediment detention accomplished by the diversion of the Jokulfall into Hvitarvatn would also be beneficial. Consideration must be given in the planning studies to an ultimate development, possibly as a second or third stage, to a higher level than 435 meters, and, if reasonably feasible economically the initial structures should be designed for later raising.

The development of Hvitarvatn, including the Jokulfall diversion for both storage and power, has been discussed by Thoroddsen[1]. The location of the storage and diversion dams are shown in plan on his Drawing No. 3812. One main dam is required across each of the two Rivers, with ancillary dikes at low places in the topography between the two. The Jokulfall dam would be located about 1.5 kilometers upstream of the mouth, where the topography is most favorable, and we agree with that location. The riverbed at the site is floored with the Grey Basalt under a thin gravel cover. The adequacy of this rock as regards strength and permeability can hardly be questioned. Both abutments would be in moraine, and the ancillary dikes would also be founded thereon.

Two alternative sites for the Hvita Dam were proposed by Thoroddsen and both are doubtless entirely in the moraine. The Upper Site is about 500 meters upstream from, and the Lower Site is about 300 meters downstream from the road bridge. The Upper Site will require two ancillary dikes, one on each side of the River, not required at the Lower Site. The bedrock is probably several meters under the riverbed at either Site, though possibly at lesser depth at the Lower Site. It probably consists of Grey Basalt, except under the right (south) abutment of the Lower Site where it may be the Breccia Formation.

Fill dams are proposed by us for all dams and dikes as probably being most economical. They may be rockfill, rolled-earthfill or a composite of the two basic types, depending on the relative suitability of available natural construction materials. Hydraulic fill construction does not appear appropriate. A high degree of impermeability of the main dams would be essential only if at-site power facilities are provided. Concrete may be economical for some segments, but the foundations where moraine will require detailed and careful study to establish their suitability beyond question.

A specific structure for diversion at each river closure may not be necessary. The general type of final closure construction used at The Dalles Dam[16] in the United States and frequently used for rockfill coffer-dams may be entirely adequate for the permanent dams. The main dams would then consist of a rockfill closure section, sealed by granular material placed under water on the upstream side, until above the water surface, and the sealing material placed by rolled-fill methods above that level. With the Hvita Dam, this procedure requires a construction rate not less than the rate of rise of the reservoir.

Inasmuch as the two alternative locations for the overall dam structure appear to present similar foundation conditions, preliminary analyses based largely on quantities and costs should permit a site selection in advance of detailed foundation investigations and permit same to be concentrated on the selected site. It is our present opinion that the Lower Site is preferable. An alternative site located farther downstream below the mouth of the Jokulfall should be considered only if neither of these two Sites develops reasonably favorably from the foundation standpoint.

It is our present opinion that the moraine will be entirely satisfactory for the foundations for the fill dams and to contain the reservoir without excessive leakage. Removal of the weathered surface, possibly for no more than one or two meters under the structures, should be adequate. As stated by Kjartansson, the moraine can be expected to be dense, hard, and reasonably watertight beneath this surface layer. Lenses of sand and gravel can be expected within the mass, but can be located by drilling and tested. They may require little or no treatment. If large leaks develop upon reservoir filling, treatment of the aquifer should not be difficult.

The topographic control point between the Jokulfall and Hvitarvatn for diversion upstream from the Jokulfall Dam is at elevation 428 meters in moraine. Diversion might reduce this level by erosion somewhat, and artificial lowering should not be necessary. Space for sediment storage is small below this control elevation and would fill quickly. A special freeboard allowance to account for the ultimate increase grade resulting from channel aggradation and to permit passing the design flood into Hvitarvatn may be necessary at the Jokulfall Dam.

Concrete would be used for the intake and outlet works and the spillway. The former would be located in the vicinity of the Hvita Dam and be designed to provide the minimum of dead storage.

Only one main spillway is required. A chute type of spillway is presently recommended. However, an ogee spillway may be provided if the final design incorporates an adequate concrete section for a portion of one of the main dams. Operational convenience in this somewhat remote area may call for an uncontrolled spillway if the increased cost of additional freeboard in the dams would be comparable with the cost of gates and hoists.

Two alternative locations are suggested for a chute spillway. One is located in the saddle about 500 meters southwest of the right abutment of the Jokulfall Dam, where basalt bedrock was exposed in the bed of the small drainage. The discharge would be into the Jokulfall. The second would be in the low saddle at about elevation 438 meters between Lambafell and Blafell, and which once served as a natural spillway for Hvitarvatn when it stood at a higher level in the geologic past. Discharge would be to the Hvita via the Lambafellskvisl. This latter spillway location would only be appropriate with the Hvita Dam at the Lower Site. At the present time, we prefer the former location for the chute spillway. The latter may represent a good site for an emergency fill-type fuze-plug spillway and result in cost savings for the main spillway.

The concrete structures within the reservoir may require some protection against icebergs. The heightened water surface encroaching against the glacier coupled with increased depths towards the south end of the Lake may permit small icebergs to form and to reach these structures.

System Operation Studies and more detailed Planning Studies, both for the Hvitarvatn and downstream power Projects, will be required to establish the initial, intermediate (if any), and ultimate developments for Hvitarvatn

Storage and Jokulfall Diversion. An initial storage development of Hvitarvatn alone to elevation 425 meters, or a meter or two higher, providing on the order of 250 million cubic meters of storage may be relatively inexpensive compared to the benefits that could accrue to even the first downstream powerplant -- and may even be required to justify such a plant.

WATER SUPPLY

A continuous, automatic stage recorder was installed on the Hvita River at the bridge below Hvitarvatn in March 1959. Another similar gage was installed on the Hvita near Aboti at the same time. The length of the records is presently inadequate for hydrological appraisals. Continuous discharge records are available since July 1949 from the gage at Gullfoss on the Hvita, where the drainage area is 2000 square kilometers, or 60 percent greater than at Aboti.

A correlation of the flow at Aboti based on 65 percent of the discharge at Gullfoss is presented in the SEA Report[9] for the period from July 1949 to August 1958. Average flows on this basis are as follows:

Period	Average Flow--kl/s
Nine years record	77
Maximum year (1953-54)	101
Minimum year (1950-51)	55
Minimum month (February 1955)	25
Maximum month (March 1953)	250

The estimated annual yield has thus varied from about 1700 to 3200 million cubic meters, with the average being 2400 million cubic meters. The yields from Hvitarvatn based solely on drainage area relationships would be about 68 percent of the above amounts. The discharge at Aboti can be considered as the sum of Hvitarvatn and the Jokulfall.

The above estimated annual yields compared to the reasonably available storage volume in the Hvitarvatn Project demonstrates clearly the great value of that storage, particularly when no other storage of comparable magnitude is feasible of development in the Hvita Basin. Further, both the Hvita and Jokulfall Rivers are glacial streams characterized generally by relatively low winter flows. The new gages will permit a closer correlation with Gullfoss and will be especially important for power and energy estimates. However, the general relationship of limited storage compared to yield is not apt to be greatly changed by the more accurate streamflow records.

FIELD INVESTIGATIONS

The available topography is adequate insofar as planning for structures is concerned. The reservoir topography should be extended to elevation 450 meters to permit a fuller evaluation of the storage potential. The sites of structures selected for design should ultimately be mapped on a scale of 1:1000 with one-meter contours. The access road should be surveyed in the design stage with a view to improving drainage, grades, and alignment.

Additional foundation investigations will be of great importance. A single boring was being made at the time of our visit to determine the depth to bedrock at the Lower Damsite on the Hvita. The initial drilling should be confined generally to the axis of the tentatively selected main dam axis. The principal purpose of this drilling will be to determine the general character of the moraine, especially its permeability. These should be churn drill holes carried to the bedrock. Extensions of each hole a few meters into bedrock with a diamond drill should be done at the site of important structures; at other locations this may be done with the churn drill. Permeability tests are of greatest importance and should be conducted in the bedrock, at regular intervals in the moraine, and at every sand and gravel lense revealed therein by the drill cuttings. These lenses are expected to be the only permeable zones of consequence. Each lense should be sampled and subjected to standard laboratory tests. Where possible, all drill holes should be preserved for groundwater table measurements in the moraine. This will probably require a perforated casing and removal of the drilling casing.

Borings should be made in the planning phase at about 50-meter centers along the axis of the site of the important structures and at 200-meter centers elsewhere along the general line of the dikes between the two main dams and beyond the abutments. Two borings should be made at the site of the proposed spillway between Blafell and Lambafell. About 20 to 25 borings should be adequate for this initial phase unless the results show the need for exploration of alternative damsites. More detailed drilling will be required in the design phase.

One or more field bearing tests of the moraine will be required if the planning should show the desirability of founding any relatively heavy concrete structures thereon.

No detailed areal geologic mapping of the area is now indicated. The stratigraphy should be developed from the results of the borings and with special reference to sand and gravel lenses within the moraine. Geologic reconnaissance for construction materials is important.

Staff gages should be installed and rated at the site of each major proposed structure crossing the two Rivers.

CONSTRUCTION MATERIALS

Requirements for concrete aggregates may not be very great if the dams are all of fill-type construction. A promising source of natural concrete aggregate and filter material exists in a large esker located near the road about three kilometers southwest of the Grjota River and about 16 kilometers southwest of the road bridge near Hvitarvatn. This esker is almost certain to contain copious quantities of suitable coarse aggregate and probably also fine aggregate. It should be sampled and tested. Reconnaissance may locate other eskers, though the haul distance from the one referred to above is not excessive. It may be advisable to establish a central plant to process aggregate from this esker not only for Hvitarvatn, but also for other Projects downstream on the Hvita.

Alternatively, basalt in the Grey Basalt Formation or intrusive in the Breccia Formation may be suitable for processing as manufactured aggregate. The Breccia Formation is probably not suitable.

Fine aggregate may also be obtained from the Jokulfall riverbed or from the Hvitarnes delta of the Fulakvisl. These sources should also be suitable for fine granular material for use in the fill dams. Rockfill shell material may be obtained from the basalts referred to above, and reconnaissance, and possibly drilling, will be required to locate a suitable and convenient quarry.

The only possible local source of rolled-earthfill or core material, other than the granular material referred to above, is the moraine. Samples of fresh and of weathered morainal material should be tested in the laboratory. Field fill tests would be of greatest importance; the main question is whether the morainal material can be handled by usual construction techniques. Generally, material which can be excavated by a power shovel should break down satisfactorily under rolling . Large boulders interspersed within the moraine would need to be removed. Blending of alluvial granular material with that of the moraine may be feasible and requires investigation and field testing.

CHAPTER VII

BLAFELL DEVELOPMENT

GENERAL TOPOGRAPHY AND GEOLOGY

The Hvita River falls about 158 meters from its origin in Hvitarvatn to just above its confluence with the Grjota (not to be confused with the other Grjota River which enters the Hvita east of Blafell) southeast of the mountain, Blafell. The river distance is about 25 kilometers. The possible power development of this reach is discussed in this Chapter. The storage development of Hvitarvatn is discussed in Chapter VI.

The Hvita through this reach flows in a hemicycle around the north, east, and south sides of Blafell, staying near the base of that mountain and keeping it always on the right side. The land on the left side for many kilometers is the gently rolling plain underlain by rocks of the Grey Basalt Formation. At the end of the Blafell reach, the Hvita takes a southwesterly course. The high gradient portion of the Blafell reach begins at the Aboti waterfall, east of Lambafell at elevation 411 meters, and rapids and small waterfalls dominate for the ensuing twelve kilometers to the foot of the island, Blafellsholmi, at elevation about 287 meters. The gradient flattens progressively from this point to the Grjota; the total fall is about 29 meters in six kilometers. The reach from Hvitarvatn to Aboti is on a flat grade. About 75 percent of the total drop in the Blafell reach is thus concentrated in the middle one-half.

Waters contributed to the Hvita by Hvitarvatn and the Jokulfall River are discussed in Chapter VI. Two principal tributaries, the Grjota and the Sanda, enter the Hvita from the east between Aboti and Blafellsholmi. They and a few other brooks entering from the left are draga streams draining areas underlain dominantly by the relatively watertight rocks of the Grey Basalt Formation. Their flow, then, is principally from surface runoff. The Grjota has a drainage area of about 90 square kilometers; the Sanda is much larger with a drainage area of about 330 square kilometers. The brooks which enter from the slopes of Blafell on the right side of the River are all quite small. The other Grjota River which drains southerly from the Langjokull ice cap and enters the Hvita beyond the lower end of the Blafell reach is not included in this discussion.

The general geology of the Blafell area is discussed by Kjartansson [(2)]. The mountains, Blafell and Lambafell, are, for the most part, formed of rocks of the Breccia Formation. The low-lying areas have the Grey Basalt as the underlying bedrock. Both formations are covered largely with moraine, and other superficial materials along the base of Blafell. The channel of the Hvita is carved in the Grey Basalt downstream from Aboti, which presents the farthest upstream exposure in the riverbed, to the end of the Blafell reach under consideration. In the deeper part of the canyon, near the upper part of Sandartunga, it has cut through the basalts and deep into the underlying Breccia Formation. Our field reconnaissance covered all of the area under consideration except that between Aboti and the mouth of the Sanda.

The available topography in the Hvitarvatn area has been discussed in Chapter VI. Topography on a scale of 1:10,000 with five-meter contours is available from Hvitarvatn downstream to the end of the Blafell reach in a strip extending from about one kilometer on the right side of the River to two to three kilometers on the left side of the River.

The single-lane motor track reaches the lower end of the section, then bypasses the remainder as it extends on the westerly slope of Bláfell to the Hvita bridge near Hvitarvatn. Otherwise the area is undeveloped and uninhabited.

DEVELOPMENT ALTERNATIVES

The physiographic, geologic, and hydrographic relationships permit such a multitude of alternatives for power development of the Bláfell reach that much additional study will be required to develop the optimum Project Plan. Our comments and recommendations can, at this time, be only general in nature. Various alternatives for power development, discussed hereinafter, are shown in plan on Exhibit 7.

A good start on the evaluation of alternatives has been made by Thoroddsen [1]. His Drawing A-1650, Sheet 14, shows in plan the development alternatives proposed. He has presented two general alternatives, with variants, to develop the entire head available. The first would develop the head in a single stage, while the second comprises two stages.

A single stage, or the upper stage of a multi-stage development, could involve an intake in Hvitarvatn and located near or within the Hvita Storage Dam, tunnel water conductors, and a powerhouse. Direct diversion from Hvitarvatn for power purposes would make diversion of the Jokulfall into Hvitarvatn virtually mandatory. With the intake in Hvitarvatn, a low-level release in the Hvita Dam would still be necessary in order to pass the flow when the power units may not be in operation. No diversion downstream from the Hvita Storage Dam for a single-stage development should be considered.

The tunnel water conductors would pass through Blafell or Lambafell, and should be of the headrace type in order to minimize water problems. They would, for the most part, be deep within the rock of that mountain. The geology along the several tunnel routes proposed by Thoroddsen is discussed by Kjartansson[(2)]. Concrete lining of any pressure tunnel in these rocks, and probably also any free-flow tunnels, will be necessary. Support during driving would almost certainly be required through substantial lengths of each tunnel. Water problems, locally severe, can be expected. On the other hand, generally favorable conditions might be encountered throughout.

Any long tunnel located so deep as to make exploration by borings from the surface prohibitively expensive presents contingent risks during construction. This is the case for any tunnel through Lambafell or Blafell; but with the additional contingency that they are both known to contain dominantly Palagonite rocks, portions of which may be very weak and permeable. The portions containing such zones would remain unknown until actual construction. Actual tunnel construction might, therefore, become excessively expensive, both in terms of time and money, as in the recent cases of the Owens River Tunnel in the United States and the Litani Tunnel in Lebanon. These risks reach a maximum with the long tunnel associated with a single-stage project to develop substantially the entire head under consideration.

The length of the tunnel water conductors from Hvitarvatn to the Hvita at the end of the Blafell section near Fremstaver would be about thirteen kilometers by the shortest alignments. Any shortening with a single-stage development, sacrificing some of the head in the lowest section of the reach, could hardly be warranted inasmuch as the head loss would more than offset tunnel savings, assuming equal tunnel driving conditions.

Any consideration of a shorter tunnel from Hvitarvatn should be confined to consideration of the upper stage of a multi-stage development. The point where such a relatively short tunnel would rejoin the Hvita would be dependent on the location of the head of the reservoir formed by the dam for the next downstream stage, which, of course, requires much further study. Thoroddsen proposed a return about three kilometers downstream from Aboti, where the water surface is about elevation 373 meters. The water conductors from the Hvita Dam at the Lower Site to that point would be about four kilometers long, and would pass through Lambafell and Blafell in following the most direct route. Other similar alternatives forming the upper stage of a multi-stage development and involving longer tunnel water conductors entering the River farther downstream may be worthy of study.

The powerhouse served by any headtunnel through Blafell might be underground if suitable rock for such a large excavation can be definitely located by drilling from the surface. This type of powerhouse would require a surge tank, individual penstocks for each unit, and a tailtunnel or tunnels. The location of these features should be established by drilling from the surface. The surge tank might be all or in part located above ground for either a surface or underground type of powerhouse. A surface powerhouse served by either underground or surface penstocks may represent more economical construction with lessened contingencies. Future enlargement may be less costly and more simple than for an underground power-station.

For reference purposes, the single-stage development is designated the Blafell Project, and the comparable first stage of a multi-stage development is designated the Lambafell Project, both as described above.

In many cases the development of at-site power from a storage reservoir is difficult to justify economically, particularly with long tunnel water conductors, because of the low capacity factor usually involved. Stored water might be released for system benefit throughout only a small portion of the year and the resulting power and energy from the at-site plant may not be firm to load except in part. This may be the case with Thorisvatn, as described in Chapter XI. However, the storage potentially available in Hvitarvatn appears to represent a small percent of the average annual yield from Hvitarvatn and the Jokulfall, so that the two storage Projects are hardly comparable as regards at-site power. Substantial releases from Hvitarvatn can be expected throughout the year with the Project still fulfilling its maximum storage functions. These releases may be near maximum during the winter months when loads should tend to be high. Therefore, with Hvitarvatn, the regulation may be an advantage rather than a detriment insofar as at-site power is concerned. Other economic factors, then, will control as to whether at-site power is developed or the Hvitarvatn storage and inflow is returned directly to the Hvita for development at downstream plants in the Blafell reach.

The single-stage development has two notable disadvantages compared with multi-stage development. One is the rather considerable head loss in the long tunnels and consequent loss of power and energy. Multi-stage development would certainly involve less head loss in water conductors and reservoir backwater, though this may tend to be offset by the economic requirement to sacrifice some small part of the total head available in the Blafell reach. Secondly, the intermediate inflow from the intervening drainage area utilizable at least in major part by multi-stage development would not be available for the single-stage development, nor could its individual development be justified in any appreciable degree. A multi-stage development, then, could generate more power and energy through the Blafell reach than could a single-stage development, assuming reasonably full development of the entire head. No statement as to the relative costs of incremental peaking capacity could be reliable at this time.

Thoroddsen(1) presented an alternative to the short tunnel of the Lambafell Project referred to above. This involved a diversion dam at Aboti and a tunnel leading to the same return point on the Hvita. Such a Project could develop nearly all of the nine or ten meters of head between Aboti and the Hvita Storage Dam. This is on the assumption of the probable certainty that the storage dam would not be located at Aboti. The variable head caused by the drawdown in Hvitarvatn and available in part or all, depending on reservoir levels, to a single-stage development would be sacrificed in its entirety. These head sacrifices may, however, be justifiable economically. The power tunnel would be about three kilometers long and, as proposed by Thoroddsen, would be a tailrace tunnel. This appears to us to be the appropriate selection, though suitable rock for the associated underground powerhouse would need to be ascertained by drilling and may result in a division of the tunnel between headrace and tailrace. The available cover does not permit a headrace tunnel throughout. This limited cover does permit relatively inexpensive drilling to develop an alignment located in the best rock. The tunnel route proposed by Thoroddsen is on the right (west) side of the River and may lie in the Breccia Formation, whereas a route on the opposite side may be in the Grey Basalts which probably present better tunneling rock. Geologic mapping, aided by a very few drill holes, should quickly establish the preferred location.

The gross head developed by the Aboti Project described above, and designated Aboti I, would be about 47 meters. This might be increased or decreased as the length of the power tunnel might be changed to best suit the level of the downstream reservoir of the second stage and on an overall economic basis. It is probable that the return point on the tunnel should not be farther downstream than the mouth of the Grjota, one kilometer farther downstream, at elevation about 368 meters, because only five meters of gross head would be gained by one kilometer of tunnel. A shorter tunnel would be more probable.

The second stage proposed by Thoroddsen would develop the remaining head in the Blafell reach to the same point as the single-stage development and is designated Sandartunga I. It would include a dam located in the deep gorge near the head of Sandartunga and about 2.5 kilometers downstream from the mouth of the Grjota. The River level at this location is about 350 meters. An auxiliary dam one kilometer to the south would cross the Sanda River and the waters of that stream would be diverted through a 600-meter long canal into the Hvita upstream of the dam thereon. The reservoir on the Hvita would extend about 3.5 kilometers to the downstream end of the Aboti tunnel at elevation 373 meters, and would receive the waters of the Sanda and the Grjota. The dam, then, would concentrate about 23 meters of head. A reservoir level to at least 385 meters appears topographically feasible at this site for a relatively small incremental cost and could shorten the Aboti tunnel by one kilometer or more, resulting in the project designated Aboti II. This dam would probably be of concrete with the River section an uncontrolled overflow spillway. The Sanda dam may be a rockfill type built of Grey Basalt from the canal excavation.

The power tunnel for Sandartunga I would extend from above the dam across the Hvita and along the right side of the River under the slopes of Blafell for a distance of about nine kilometers. It would be located in the Breccia Formation throughout. The comments made above for the tunnels and other power features of the single-stage development apply almost equally here and need not be repeated. The elevation of the Hvita at the point where the water would be returned is about 263 meters, thus 110 meters of gross head would be developed with a reservoir at elevation 373 meters, and 122 meters with the headwater at elevation 385 meters.

Alternatively, the tunnel could return to the Hvita at the lower end of Blafellsholmi where the water surface is about elevation 287 meters, which would shorten the tunnel length to about 6.5 kilometers while leaving about 24 meters of head for other development, or sacrificed. This project is designated Sandartunga II. With an underground powerstation located intermediately along a tunnel route relatively close to the River on one side or the other, it should be economically feasible to explore the subsurface conditions along the headrace and tailrace tunnels and at the powerstation and other excavations by drilling from the surface. These excavations would be largely in the Breccia Formation if located to the right of the River, but substantial portions may be in the Grey Basalt Formation if located to the left of the River. The latter Formation may be the more desirable.

A third alternative for the second stage of a multi-stage development would have the tunnel return to the Hvita about three kilometers downstream from the dam, where the water surface is about elevation 325 meters. The tunnel would be only slightly longer, about 3.5 kilometers. This alternative is designated Sandartunga III. The comments made above with respect to the power features for a tunnel extending to Blafellsholmi apply generally to this shorter power tunnel route. The exploration depths would, however, be much less inasmuch as the tailtunnel and powerstation would be positioned about 38 meters higher. This higher level may place most of the underground features in the Grey Basalt. The headtunnel would be at the same level, but it and the required surge tank might be replaced by individual penstocks leading directly from the intake if suitable conditions for the powerstation are found adequately close. The gross head with this latter plan would be about 48 meters for a reservoir at elevation 373 meters.

Sandartunga III would require a third stage in the Blafell reach, designated the Blafellsholmi Project. The dam would be located at or near the upper end of the Blafellsholmi Island where the water surface is about 310 meters. The dam would be located in a range of about one kilometer centered at the mouth of the Sanda, depending on the results of economic analyses as to this overall possible third stage. No dam across the Sanda is required with a dam on the Hvita upstream of the former's mouth inasmuch as inflow downstream from the diversion dam located thereon is negligible. The reservoir would be at elevation about 325 meters, tailwater of Sandartungs III.

The River drops about 23 meters in about one kilometer as it divides around Blafellsholmi, and the grade downstream therefrom flattens appreciably. Whether all or part of this latter drop may be economically developed by the Blafellsholmi Project is questionable and must be the subject of further studies.

At this time, we will consider that only the head to the lower end of Blafellsholmi will be developed by the third stage project. Several alternatives for the power features may be considered. The same underground plan proposed above for Sandartunga III is one possibility. Alternatively, surface penstocks leading to individual surge tanks and a surface powerhouse located at tailwater may be considered. If the dam is located just downstream from the upper end of Blafellsholmi Island, and the spillway placed in the left channel, the penstocks may be laid in the dry bed of the right channel, possibly with some short tunnel sections. These and other possibilities should be studied in the planning stage.

This site was visited during our field reconnaissance. Exposures of the Grey Basalt Formation only were observed, and it is reasonably safe to assume that that formation would be encountered by any subsurface excavations.

A gross head of about 38 meters would be developed by the Blafellsholmi Project. There thus remains about 24 meters of head downstream to the return point of the single-stage development which must be developed by other means or sacrificed as uneconomical. No studies have been made of damsites in this lower reach. A possible damsite, located about 2.5 kilometers downstream of Blafellsholmi, was observed in the field and noted on the topography. The head would be about 17 meters. The powerhouse may be contiguous with the dam with tailwater at elevation about 270 meters.

The low gradient extending downstream does not hold promise for gaining head economically by a tunnel or canal. There is, however, a possibility that about 18 meters of additional head, to elevation about 252 meters, may be gained by water conductors about four kilometers long entering the Hvita about two kilometers upstream of the point where the Sanda River from Lake Sandvatn enters the Hvita. The topography indicates that a canal route may be technically feasible. This arrangement would provide a total head of about 35 meters, but the overall economics appear questionable. The topography indicates that a dam located about one kilometer downstream of the mouth of the Grjota River may be constructed to develop most of this same head. However, it would be over one and one-half kilometers long and reach a maximum height in excess of 25 meters. Foundation conditions, however, should be favorable. For reference purposes a possible Project in this general area is designated the Fremstaver Project.

The first engineering step with respect to the study of power development of the Blafell reach will be an appraisal study made on a comparable basis aimed to permit a definite selection between single-stage and multi-stage development of the resource. We believe that we have outlined above all of the individual but related alternatives for the Projects of the multi-stage development worthy of consideration in the appraisal study. The study itself, and more detailed field investigations may, however, reveal some additional alternatives worthy of analyses.

The specific cost of the Hvitarvatn Storage Project including the Jokulfall Diversion as presented in Chapter VI should be excluded from the comparison.

The construction of that storage and regulation Project will doubtless precede power development of the Blafell reach. Its benefits will accrue to all power developments downstream on the Hvita in some proportionate manner. Projects on the Blafell reach may, when constructed, be called upon to share on some equitable basis a proportion of the annual costs of the Hvitarvatn Project, but this feature does not need to enter the comparisons referred to above. It appears almost certain that any power development in the Blafell reach requires the benefit of the Hvitarvatn storage and flow regulation to be justified economically.

Important data with respect to individual Projects of the various development alternatives outlined above are tabulated below on an approximate basis. Roman numeral and letter designations assigned various of the possible Projects are based on gross head and/or water conductor length variations. The Fremstaver Project as a possible third or fourth stage of a multi-stage development is not included. Its consideration should probably not enter the comparison between single-stage versus multi-stage development of the Blafell reach.

PROJECT DATA

Project	Headwater Elevation-Meters	Tailwater Elevation-Meters	Gross Head-Meters	Water Conductor Length-Kilometers	Dam (1) Height - Meters
Blafell	435 (2)	263	172	13	-
Lambafell	435 (2)	373	62	4	-
Aboti I	420	373	47	3	10
Aboti II	420	385	35	2	10
Sandartunga I	373	263	110	9	23
Sandartunga I A	385	263	122	9	35
Sandartunga II	373	287	86	6.5	23
Sandartunga II A	385	287	98	6.5	35
Sandartunga III	373	325	48	3.5	23
Sandartunga III A	385	325	60	3.5	35
Blafellsholmi	325	287	38	0.8 - 1.3	12 - 17

(1) Based on reservoir - river surface differences only

(2) Based on tentative Hvitarvatn maximum level

Each proposed Project, other than Blafell, is a unit of a multi-stage development. The previous discussion relates the several variants one to the other. For example, a two-stage development could include Aboti I and Sandartunga II, while a three-stage development could include Aboti I, Sandartunga III, and Blafellsholmi.

A multi-stage development involving dams and short tunnels near enough to the surface to permit exploration by drilling can be estimated to closer relative accuracy than either the single-stage development or two-stage developments having long tunnels deep underground in the Breccia Formation comprising Blafell. Long tunnels under those conditions, such as for Blafell, Lambafell, and Sandartunga I, carry a high contingent risk which must be allowed for insofar as adequately possible within the comparative estimates. Assuming nearly equivalent unit or total cost relationships made on that basis between the single-stage and multi-stage developments, the conservative approach would be to adopt a multi-stage development with a relatively low contingent risk such as Abot II, Sandartunga III A, and Blafellsholmi, or their variant equivalents.

A three-stage development of this type has the additional important advantage of permitting progressive construction of relatively smaller Projects, both in cost and capacity, which may better fit the pattern of system load growth. Each of these three Projects, or reasonable variants thereof all considered as a system, are believed to be positioned in reasonably good rocks without serious construction problems. The second two in order of construction could be "slave" plants remotely controlled from the first to be constructed. While we have not made any cost analyses, we presently believe that each would, with Hvitarvatn storage, develop power and energy at relatively favorable unit costs. These unit costs based on delivery at Reykjavik may be no greater than those of, say, power plants on the Tungnaa River.

WATER SUPPLY, POWER AND ENERGY

The water supply available to Hvitarvatn is discussed in Chapter VI. This supply would be that available to the Blafell and Lambafell Projects and for all practical purposes, to the Aboti Project. The Sandartunga Project would receive the inflow from the two tributaries, the Grjota and the Sanda, and some other brooks, with a total drainage area on the order of 450 square kilometers. No flow records are available for this specific drainage. The average annual discharge based on drainage area relation with the Gullfoss record would be about 25 kl/s. The increment to the Blafellsholmi Project over that for Sandartunga is almost negligible for power and energy estimates. The estimated average annual flow available to Hvitarvatn, including the Jokulfall, was 77 kl/s, and thus the estimate for Sandartunga and Blafellsholmi would be 102 kl/s. Storage on the Sanda or Grjota does not appear feasible, but a possible damsite on the Sanda above the rapids near Mikluoldubotnar should be studied.

The estimated ultimate installed capacity and gross average annual energy production for each of several representative Projects is tabulated below. These estimates are based on the average annual flows, plant capacity factors of 70 percent with such flows, and allowances for head losses resulting from tunnel friction and storage drawdown.

ESTIMATED PROJECT POWER AND ENERGY

Stage	Project	Average Annual Discharge Kl/s	Station Flow Capacity Kl/s	Gross Head Meters	Installed Capacity Kilowatts	Gross Aver. Annual Energy Million kwh
Single	Blafell	77	110	172	135,000	840
Two	Lambafell	77	110	62	50,000	300
	Sandartunga I	102	145	110	115,000	720
	Total Two-Stage			172	165,000	1 020
Three	Aboti II	77	110	35	30,000	180
	Sandartunga III A	102	145	60	65,000	400
	Blafellsholmi	102	145	38	45,000	260
	Total Three-Stage			133	140,000	840

The above approximate analyses, based on roughly estimated but generally comparable data, demonstrate that the installed capacity and gross average annual energy production of the three-stage development which sacrifices some head is nearly identical to the single-stage development. The two-stage development utilizing the entire head increases the related gross annual energy production by about 180 million kilowatthours principally because of utilization of the incremental flow. Other Projects or variants and combinations thereof can be quickly analyzed from the above table by direct gross head proportions with reasonable accuracy. The above analyses are illustrative primarily, but tend to further emphasize the apparent advantage to three-stage development or a limited two-stage development such as Aboti I and Sandartunga II, of the Blafell reach.

FIELD INVESTIGATIONS

Additional field investigations to accomplish the appraisal outlined above need not be extensive. The existing 1:10,000 scale topography is generally adequate but should be supplemented by surveyed profiles at the damsites and at the Sanda River Diversion Canal. Several profiles will be needed at the proposed Blafellsholmi damsite, though it may be nearly as economical and more satisfactory to map the area on a scale of 1:1000 with one-meter contours. Further general geologic reconnaissance should be accomplished at the site of the major structures mostly to relate the stratigraphy to the maps and profiles recommended above, and to observe any special conditions of significant engineering importance. Subsurface exploration does not appear essential. If any is accomplished, it should consist of only a few holes to establish foundation conditions at the tentative site of such important underground structures as powerstations, and to provide a general knowledge of the stratigraphy along proposed tunnel routes.

Additional field investigations during the planning and design stages are essential. They would consist generally of large-scale topography at the site of all structures, access road surveys, foundation exploration with special emphasis on permeability and strength of stratigraphic units, geologic mapping especially of the stratigraphy along tunnel routes, and reconnaissance for construction materials. Exploratory shafts, drifts, and tunnels may be necessary. Staff gages should be established and rated at the selected damsites and tailraces.

CONSTRUCTION MATERIALS

The comments relative to construction materials in Chapter VI, relative to Hvitarvatn, apply almost equally to the Bláfell Development and are not repeated here. In addition, the bed of the Sanda River near Sandartunga may yield suitable natural construction materials.

CHAPTER VIII

GULLFOSS DEVELOPMENT

GENERAL TOPOGRAPHY AND GEOLOGY

The Gullfoss Reach, as designated herein, is that portion of the Hvita River which extends from the lower end of the Blafell Reach, at elevation 263 meters, for 57 kilometers to the mouth of the Bruara River, at elevation 50 meters - the approximate level of the Hestvatn Reservoir, described in Chapter V. The development of the Blafell reach is described in Chapter VII.

The Gullfoss Reach is, for hydroelectric power development discussion, divided into four Sections designated, the Sanda, Gullfoss Gorge, Haukholt, and Skalholt Sections, proceeding from upstream to downstream, respectively. Each of these Sections is briefly described:

1. The Sanda Section

This uppermost Section extends from the lower end of the Blafell Reach for thirteen kilometers to the mouth of the Budara River, at elevation 227 meters. The countryside through this Section is open and rolling. The Sanda River, through which the waters of Lake Sandvatn may be diverted to the Hvita, enters from the west midway through this Section.

The total fall in the Sanda Section is about 36 meters. The fall above elevation about 252 meters may possibly be developed by the proposed Fremstaver Project, described in Chapter VII. The lower portion of the Section to about elevation 242 meters would be occupied by the reservoir of the Gullfoss Project, hereinafter discussed. The remaining ten meters of fall in the Sanda Section do not now appear feasible of development.

2. The Gullfoss Gorge Section

This high gradient Section extends from the mouth of the Budara River for about ten kilometers downstream to a point three kilometers upstream from the Bruarhlod Bridge. The total fall is about 125 meters. The Hvita River in this Section is confined in a deep and narrow canyon carved in the rocks of the Grey Basalt Formation by post-glacial erosion.

A continuous, moderately uniform rapids extends from the mouth of the Budara River for 4.2 kilometers downstream to elevation 189 meters at the head of the famed waterfall, Gullfoss. The average gradient of the rapids is about nine meters per kilometer. Gullfoss has a nearly vertical drop of about 30 meters, split between two nearly equal steps. The Hvita downstream is confined to an inner gorge, with the low west wall about 40 meters high. The rapids resume downstream from the foot of Gullfoss and extend for 5.5 kilometers to a River level of 102 meters at the end of the Section. The average gradient of these downstream rapids is about ten meters per kilometer, and the gradient flattens somewhat proceeding downstream from Gullfoss.

3. The Haukholt Section

The Haukholt Section begins with a sharp break in the River profile at the end of the Gullfoss Section and extends for ten kilometers downstream to a River level of about 69 meters. The Hvita through the Section continues to be confined within the canyon, but the height of the canyon walls becomes progressively less. The gradient through the Section likewise becomes progressively more gentle proceeding downstream, and the total fall is about 33 meters.

4. The Skalholt Section

The Skalholt Section begins at the end of the Haukholt Section, where the Hvita leaves the canyon, and flows for 24 kilometers at a low gradient through open country to the mouth of the Bruara River. The total drop is only about 19 meters. None of this Section is now considered feasible for hydroelectric development. The Tungufljot and Stora-Laxa Rivers add their waters to the Hvita within the Skalholt Section.

The Hvita River from the lower end of the Blafell Reach flows southwesterly in a remarkably straight course to and beyond its confluence with the Bruara, and through the Sections described above. Being straight, it is also narrow until it widens and begins to meander with the low gradient beyond the lower end of the Gullfoss Gorge. The riverbed is carved in basalt flows and sedimentary interbeds of the Grey Basalt Formation wherever observed throughout this entire area.

The bedrock is covered locally with moraine and other superficial materials, including loessic soil which provides extensive grazing lands to the south and west of Gullfoss. No detailed geologic study with a view towards power development has, to our knowledge, been accomplished for the Gullfoss area.

The spectacular waterfall, Gullfoss, is one of the major and popular scenic attractions of Iceland. It is served by a good gravel road extending 100 kilometers northeastward from Reykjavik. Some tourist facilities are available and serve the thousands of tourists who come in the summertime to view Gullfoss. While some sentiment doubtless exists to preserve the falls in an untouched manner, power development coordinated to preserve or even enhance the scenic beauty inherent with natural waterfalls has gone forward with many waterfalls throughout the world. We assume that some definite policy with respect to such coordination would need to be evolved before design or construction of any power features at Gullfoss.

All or nearly all of the area which would include the engineering features of a power development in the Gullfoss Gorge Section is covered by recent topography on a scale of 1:2000 with two-meter contours. This mapping includes most of the potential reservoir under the 244-meter contour in the Sanda Section, the vicinity of potentential damsites up to that level for about 2.5 kilometers downstream from the mouth of the Budara, and a strip on the left (southeast) side of the River up to 1.5 kilometers wide beyond the brink of the gorge except in the vicinity of Nautavik, four kilometers below Gullfoss, where it extends to or near the left water's edge for a length of 1.5 kilometers.

The general area of the Gullfoss reach was covered by our field reconnaissance.

DEVELOPMENT ALTERNATIVES

General

The head concentration in the waterfall, Gullfoss, and the contiguous rapids, together with the favorable geologic setting provides the opportunity for the relatively economical development of power and energy with a transmission distance of somewhat less than 100 kilometers to the Reykjavik load center. Two, or possibly three, separate projects appear feasible. The uppermost Project, designated the Gullfoss Project, would develop all or nearly all of the head on the Gullfoss Gorge Section plus the head in the lower portion of the Sanda Section. A second Project, designated the Haukholt Project, would develop most of the fall in the Haukholt Section plus any fall in the Gullfoss Gorge Section left undeveloped by the Gullfoss Project. This same total fall might, alternatively, be developed by two Projects instead of the single Haukholt Project.

The Gullfoss Project

The moderately high head with the flow regulated by the Hvitarvatn Project means that the Gullfoss Project should be developed ultimately as a peaking plant operating at a relatively low annual plant capacity factor. The cost of incremental capacity would almost certainly be in a favorable range. There must be provided, then, a reservoir containing adequate pondage.

The development of the drop at the waterfall, Gullfoss, together with that in the rapids upstream and downstream can be best accomplished with a dam upstream of the waterfall diverting the water through a tunnel or tunnels to a tailrace point within the rapids downstream. A development of this general type was proposed by Thoroddsen[1] and is shown in plan on his Drawing A-1484, sheet 9. More detailed studies will be required, as hereinafter discussed to determine the optimum head to be developed, and the optimum headwater level.

The most favorable location for the dam on the Hvita is about 1200 meters downstream from the mouth of the Budara, where the water surface is about elevation 210 meters. The alternative site located about 800 meters upstream, proposed by Thoroddsen, appears to us to be less favorable than the recommended site, but should be evaluated on a comparable basis during the planning phase. The recommended site would require a dam of about eight meters greater height for an equal reservoir elevation, but the required volume and overall Project costs should be less. The length of the water conductors would be reduced by nearly a kilometer, and the deeper level available for the intake would have advantages with respect to ice problems.

No other damsites located upstream from Gullfoss appear worthy of study for the Project. The topography between the head of Gullfoss and the recommended site is unfavorable in that a dam to develop adequate head and pondage would be of relatively excess volume. No topographically favorable damsite exists in the Section upstream of the mouth of the Budara, or in the rapids downstream of Gullfoss.

Detailed planning studies are required to permit the selection of the structural type of dam and arrangement of the principal features. The topography and geology at the recommended site favors concrete arch construction with gravity thrust blocks. Short wing dams might be required at each abutment beyond the thrust blocks. The intake would be on the side most favorable to suit the other power features, and would probably be on the left (southeast) side. It might be a structure separate from the dam features, or incorporated therein.

The spillway arrangement with an arch dam would require study during the planning phase. The spillway could be of the uncontrolled type inasmuch as there appears no requirement to limit reservoir levels other than to necessary freeboard on the non-overflow structures. Comparison would need to be made to the cost of providing gates for control of all or part of the design spillway capacity. The spillway may discharge over the arch dam if energy dissipation works are of reasonable cost. Alternatively, a chute spillway, positioned beyond the thrust blocks, may be more economical. A ski-jump type of energy dissipator appears appropriate.

Low-level release gates or valves will be required to pass sediment and to release water to preserve in some degree, at least at times, the scenic values of the Gullfoss waterfall. However, spillway gates (if provided) may be less costly for this latter purpose. The low-level releases may be incorporated in the main dam or within the diversion tunnel. That tunnel, however, may not be required with concrete construction which at this site permits great flexibility for diversion through low blocks.

Other standard types for the dam must be considered during the planning phase as alternatives to the concrete arch construction proposed above. Alternative structural or mass concrete types or combinations thereof such as gravity, multiple-arch, massive buttress, or slab and buttress should be investigated. The comments made above with respect to the auxiliary features, such as intake, spillway, low-level releases, and diversion, apply generally to these concrete types of alternative construction. Fill-type construction must also be considered and may include rockfill or composite rockfill and earthfill. Rolled earthfill or hydraulic fill are not considered appropriate. The aforementioned auxiliary features are all required for fill-type construction of the main dam, but their type and arrangement may, in part, be different than for concrete construction.

Special features to minimize ice problems will be required regardless of the main dam type or location. These features, for the most part, would be associated with the intake and the spillway.

It is our present opinion that concrete arch construction for the main dam at the recommended site will be the most economical selection. Arch construction for the alternative site located upstream is considered less appropriate, but the other types suggested above, either singly or in combinations, may be studied.

The normal reservoir level as controlled by the dam must be determined by economic dam height analyses. The initial reservoir level should not, in our opinion, be less than elevation 238 meters, assuming that the initial power installation would be for a relatively high capacity factor, because any lower elevation would not provide adequate daily pondage without excess head reduction. The level should not be less than 242 meters for an ultimate installation of a relatively low capacity factor in order to provide adequate pondage. A higher level than 242 meters may be justified by (a) the benefits from increased head, or (b) the requirement for more pondage with an extremely low ultimate plant capacity factor such as 25 percent. A level much above about 244 meters would bring on the requirement of a dike or dikes for a total distance of one kilometer or more to enclose the reservoir rim to the northwest of the main dam. A dike would be required in the lowest saddle located about one kilometer to the northwest for any reservoir above about elevation 236 meters. We propose rockfill construction for the dike or dikes as probably being the most economical type.

It is probable that a reservoir level for any ultimate development in excess of 244 meters cannot be justified inasmuch as that level would provide adequate pondage, and higher levels would represent only the purchase of head at a high price when the cost of the added height and length of dikes and of other features is included. The dam height analyses should, therefore, cover the range of levels between 236 and 246 meters. The analyses could be accomplished adequately on the basis of a single basic dam layout. We suggest the concrete arch dam plan at the recommended site for this purpose. It is our present opinion that the analyses will show that a level between elevation 240 and 242 meters can be justified for the initial Project, and that the higher of the two levels will provide adequate pondage for a low capacity factor ultimate plant.

The River profile relationships discussed above mean that some head in the reach upstream from the upper end of the reservoir for the Gullfoss Project may never be economical of development for power purposes. The economically questionable Fremstaver Project, discussed in Chapter VII, could develop down to elevation 252 meters, leaving ten meters or more of head undeveloped. It is recognized that the head available on the Hvita between the Gullfoss Project and the lowest development constructed in the Blafell reach may, at some future time, need to be considered for power development, but we do not believe that any specific studies are justified in the forseeable future.

The full diversion of the waters from Lake Sandvatn to the Hvita via the Sanda River to augment the flow available to the Gullfoss Project appears, on the basis of the small-scale maps, to be attractive. These maps indicate that the Sanda may receive some waters from Sandvatn during high flow periods, but that most of the flow goes to the Tungufljot River. Small dams of fill construction located across the two southerly outlets of Sandvatn should be relatively inexpensive and could divert substantially all of the discharge to the Sanda River. Controlled regulation may not be justified; Hagavatn and Sandvatn may already provide a high degree of natural regulation. This diversion should be studied as a part of the Gullfoss Project and may have an important bearing on the plant installed capacity.

Planning studies are required to establish the optimum amount of head to be developed by the Gullfoss Project, and the initial and ultimate capacity installations to be provided therein. A headwater level of 242 meters is selected solely for the following discussion. Tunnels represent the logical choice for the main water conductors. Thoroddsen [1] proposed an underground powerstation with the tailtunnel discharging at Nautavik, about four kilometers downstream from the Gullfoss waterfall, where the tailwater would be about elevation 114 meters. The gross head would thus be about 128 meters. Development to this point should be studied further. The overall length of the water conductors would be about seven kilometers with a headtunnel type of development and the dam located at the recommended site.

The water conductors could be lengthened to discharge farther downstream and utilize more head. It would probably not be economic to develop farther than to a tailwater elevation of 102 meters, providing 140 meters of gross head, with an increased tunnel length of about 1.5 kilometers. The gradient downstream from this point flattens appreciably and becomes less favorable for development by tunnels. On the other hand, it may be more economic to develop less total head, with tailwater at some point upstream from Nautavik, but below the foot of Gullfoss.

The planning studies would establish the optimum combination of powerstations and water conductors for the Gullfoss Project, and various alternatives should be investigated. The powerhouse may be above ground at the selected tailwater point with penstocks connecting to each unit from a surge tank at or near the end of a long headtunnel. The penstocks may be either above ground or in tunnels, with the latter preferred in view of expected generally good tunneling conditions. The surface type of powerhouse may present advantages with respect to the installation of future incremental capacity because of possible lower initial investment compared with an underground installation. This may be offset by the cost of required protection against high tailwater under severe ice conditions. Ice conditions may be different than at present, especially with another reservoir located downstream from tailwater.

An underground location must be considered for the powerstation. It might be positioned in any geologically favorable location along the tunnel route or routes. It may be located to provide the maximum length of head-tunnel permitted by the topography with consequent minimum length of tail-tunnel, generally as proposed by Thoroddsen(1). Alternatively, it may be positioned very near the main dam with each unit served by individual penstocks connecting directly from the intake. The tailtunnel would be of maximum length with this latter arrangement. A more equal division between relative lengths of headtunnel and tailtunnel between the two extremes mentioned above must also be considered. In any event, the ultimate choice may be determined largely on the basis of fitting the underground excavations to the overall best rock within the sequence of the Grey Basalt Formation. Drilling and geologic studies will be of great importance in this regard.

The tunnel location and design will vary somewhat with each of the various powerhouse alternatives referred to above. Reinforced concrete lining may be required for structural support along some portions, probably minor, of any tunnel. Some support of the underground excavations during driving will be necessary, but should not be great in view of the probable good quality of the rock. The headtunnel and penstocks would be under pressure and should be concrete lined throughout to assure watertightness and probably also for overall economy. The planning studies should assume concrete lining of any surge tanks located in underground excavation. Steel lining would be required for any penstocks wherever the cover is inadequate. Tailtunnels should probably not require concrete lining except where needed for permanent structural support.

The headtunnel alignment for any alternative must provide adequate cover. This will require a location on the left (southeast) side of the River throughout. A powerstation served directly by penstocks from the intake may be placed on either side of the River with little difference in tunnel length. The tailtunnel would cross under the River, with the powerstation on the right side, but at a depth that should present no additional water problems. Station access might be less costly on the right side. The nearly straight alignment from dam to tailrace, apparently possible, could reduce the overall length of water conductors by several hundred meters when compared with a long headrace type of development.

The number of units and their installed capacity, both initially and ultimately, would be established by the planning studies and System Operation Studies. We believe that the initial installation should not be less than two nor more than three units. Provision for future incremental capacity should be based on one or two units, depending on the indicated capacity position the Project may occupy in the future of the Power Supply System. Converting the Gullfoss Project to an exceedingly low capacity factor plant might be indicated to be so far in the future as not to permit the justification of initial provisions almost solely for that purpose.

Thoroddsen(1) proposed the diversion by tunnel of the Hvita to the Tungufljot River as an alternative to returning the waters to the Hvita near Nautavik. The water conductors would be about three kilometers longer, but 19 meters of gross head could be gained. It is our present opinion that this alternative should not be studied further unless subsequent detailed studies of possible downstream development on the Tungufljot may indicate the desirability of more detailed analyses based on such diversion and coordination.

It is our present opinion that the optimum power development of the available head below the level of the proposed headwater at the Gullfoss Project would be accomplished with tailwater at or somewhat below Nautavik. This should be verified, however, by planning studies which would include studies of the various alternatives discussed above.

The Haukholt Project

The optimum head to be developed at the Gullfoss Project should be considered in coordination with the relative economics of developing some portion of the remaining head immediately downstream. It does not now appear that any of the available head between the mouth of the Bruara, at elevation 50 meters, and the site of a possible low dam for the Haukholt Project near the farm by that name, towards the lower end of the canyon where the water surface is about elevation 77 meters, is feasible for economical development in the foreseeable future. Accordingly no studies for development of this 27 meters of head are suggested at this time.

Based on our reconnaissance and the small-scale maps, the topography and geology at the Haukholt damsite appear reasonably favorable for head development to a maximum of about elevation 115 meters. The economic level of development when considered in relation to the Gullfoss Project may be somewhat less and should be studied. These studies may possibly show development at Haukholt to be economic, ultimately, to between about elevations 102 and 114 meters, the range of possible tailwater elevation referred to above for the Gullfoss Project with long tunnels.

The optimum overall development of the Gorge reach of the Hvita for power may call for the development of lesser gross head than 128 meters at the Gullfoss Project, with some or all of the remaining head concentrated at a downstream dam or dams with contiguous powerstations. The tailwater for the Gullfoss Project would be at higher elevation upstream from Nautavik, with consequent shorter water conductors. The next dam downstream, with headwater coincident with Gullfoss Project tailwater might, because of topographic considerations, need to be located farther upstream than the Haukholt Site inasmuch as head sacrifice does not appear warranted. Head available even farther downstream might be developed by a lower dam at Haukholt or somewhat down the River therefrom. Other damsites exist upstream from Haukholt Site. The inner gorge of the Hvita is generally uniform in cross-section and geology to about 30 to 40 meters above the water surface. The geology and topography between Gulfoss and the Haukholt Site appear favorable for concrete arch construction. Detailed topography, however, is not available.

The Haukholt Project, or other alternative projects in that general area, would probably consist of a concrete overflow dam with a contiguous surface powerhouse served by penstocks from an intake incorporated in the concrete dam. The Gullfoss Project would probably be constructed first.

WATER SUPPLY, POWER, AND ENERGY

Continuous discharge records of the Hvita River are available from the gage at Gullfoss since July 1949, and are presented in the SEA Report(9). Important data from these records follows:

Item	Discharge-kl/s
Average Annual Discharge (8 years)	118
Average Discharge - Minimum Year (1950-51)	84
Average Discharge - Maximum Year (1953-54)	156
Minimum Average Monthly Discharge (Feb. 1955)	38
Maximum Average Monthly Discharge (March 1953)	384
Minimum Average Weekly Discharge	31
Maximum Recorded Flood	586

The average annual yield on the basis of the record would be about 3.700 million cubic meters. The annual yield has varied between about 2600 and 4900 million cubic meters.

The flow of the Hvita at Gullfoss is not dominated by any of the single hydrologic influences which, one or the other, tend to dominate so many of the comparable sized streams in Southwest Iceland. Its flow is a combination of glacial meltwater, largely regulated by Hvitarvatn, and the contribution of draga tributaries. As a general rule, fall and winter flows are low and spring and summer flows are relatively high. High flows, however, may occur any month of the year but, on the other hand, the flow during any month may be less than the average annual discharge. The variability points to the need for Hvitarvatn storage, and the planning studies should be on the assumption that the storage will be provided prior to or shortly after the Gullfoss Project may come into operation.

There are no known discharge records for the two outlets of Sandvatn to the Tungufljot River. Records of this River are available since August 1951 from a staff gage located at Faxi where the drainage area is 720 square kilometers, The drainage area above Sandvatn is 566 square kilometers, of which 270 are covered by the glacier, Langjokull. These areas must be considered somewhat approximate. The average discharge of the Tungufljot at Faxi is 47 kl/s, according to the SEA Report[9], and the flow of this naturally regulated linda river is moderately uniform. We consider that the average flow at the outlets of Sandvatn may total less than would be computed on the basis of the 80 percent drainage area proportion with Faxi. Some discharge check measurements are required to establish a correlation with the record. We have tentatively chosen, without much real basis, a value of 22 kl/s for the average flow which may be diverted to the Hvita from Sandvatn as proposed above. This would bring the average annual flow of the Hvita to an estimated 140 kl/s as available to the Gullfoss Project.

We believe, on the basis of our study of the flow records and considering the diversion of Sandvatn and regulation at Hvitarvatn, that the initial installed flow capacity at the Gullfoss Project should be on the order of 200 kl/s. Ultimate conversion of the Project to a peaking plant primarily may raise this installed capacity to as much as double that amount. The corresponding initial installed capacity would be about 200,000 kilowatts with tailwater at Nautavik.

The gross average annual energy on this same flow and head basis would be above 1200 million kilowatt-hours. However, it may be required that some of the inflow be released to assist in preserving Gullfoss as a scenic attraction, and this water would be lost for energy production. Some waterfalls are considered more attractive with lower rather than higher discharge. The famed Niagara Falls between the United States and Canada is controlled by treaty to provide approximately one-half of the average annual flow over the falls by day and one-fourth by night. At other natural waterfall power developments, remote from populated areas, some relatively constant flow is provided during the summer tourist season only. This might be feasible at Gullfoss where the daylight periods in the summer are long. A release of, say 25 kl/s, approximately equivalent to the possible diversion from Sandvatn, released for about four months in the summer would reduce annual energy production only about six percent. Power capability should be little affected.

FIELD INVESTIGATIONS

Some additional topography will be required to permit an adequate evaluation of the Gullfoss Project in the planning phase. This would include mapping on a scale of 1:2000 with one-meter contours of the damsites and of the outlet for the proposed Sandvatn Diversion. Extension of the existing large-scale topography to include the Hvita Gorge below elevation 125 meters between Nautavik and the proposed Haukholt damsite would be helpful. However, further field reconnaissance may reveal that a few surveyed cross-sections would be adequate for appraisal purposes. Some surveys will be required in connection with the geologic mapping of the stratigraphy. The existing large-scale topography should also be extended to include the reservoir and required dike locations up to elevation 250 meters. A minor amount of additional topographic detail is needed at the recommended damsite on the Hvita, and again one or two cross-sections may be adequate. All cross-sections everywhere should be located in plan with reference to existing topography and contain specific stratigraphic measurements.

Subsurface borings will be required and, initially, would be aimed to obtain: (1) foundation information at the proposed damsites, and (2) stratigraphic information. A minimum of four diamond drill holes should be drilled at each of the two Hvita damsites, Gullfoss and Haukholt. Two borings in the riverbed and one in each abutment are required initially at each damsite to establish general permeability relationships and strength characteristics with specific regard to possible arch type construction of the dams. The Sandvatn area was not covered by our field reconnaissance, but we suggest a minimum of two holes at each damsite, and at the Sanda River outlet. These borings may show the need for further drilling at each damsite. Stratigraphic information from each drill hole in or near the Hvita will be important.

Mapping of the structure and stratigraphy of the exposures of the Grey Basalt sequence through the Hvita Gorge from the mouth of the Budara to below Haukholt should represent the initial geologic studies for the proposed Projects. A number of measured cross-sections which would be located in plan on the existing large-scale topography may represent the most expeditious method. Correlation of individual members of the sequence will be required throughout. Several diamond drill holes are required to permit reasonable extension of the geology from the surface exposures to the vicinity of all underground power features proposed for study. The number and location of these drill holes, for the most part, can be best established after completion of the areal geologic mapping. A few holes such as at the location of proposed underground power-stations may proceed at the same time as the areal geologic mapping and would serve a dual function. A total of ten or more deep borings will probably be required. Special study will be required of basalt flows and sedimentary beds which may be expected at the level of underground excavations, and will include study of the core and of the exposures where possible.

The results of these borings should provide information required to select the optimum plan of development for the Gullfoss Reach. The next engineering step would be to more clearly define the selected Project Plans to permit detailed design and construction, and would include additional mapping and subsurface explorations. The location of surface structures should be mapped on a scale of 1:1000 with one-meter contours. The location of underground excavations would need to be explored in reasonable detail to the depths involved. Additional drilling will be required at the selected damsites. The area on the right side of the River for a width of one kilometer or more between the waterfall and the damsite for the Gullfoss Project should be mapped on a scale of 1:20,000 and with five-meter contours. This should include possible access routes, camp, and construction plant areas.

Staff gages should be established and rated at all potential damsites and tailrace points.

CONSTRUCTION MATERIALS

The large esker, referred to in Chapter VI, may represent the most favorable source of material for processing into concrete aggregates and filter material. The haul distance is only about ten kilometers from the proposed Gullfoss dam. If fine aggregates are not contained therein, field reconnaissance will be required to locate a suitable deposit. The Sandvatn area appears favorable for the northern end of the Gullfoss Reach.

Concrete for power features located towards the south end of the Reach may require aggregates from that vicinity. There may be ancient shoreline deposits within reasonable haul distance and the geologic reconnaissance should explore this possibility. Fine aggregates may be available in the riverbed downstream from the lower mouth of the Hvita Gorge.

The basalts prevalent in the overall area are considered suitable for processing into rockfill, concrete aggregate, and filter materials.

A good source of core material was not revealed by our reconnaissance. Some of the loessic soils may be suitable, particularly if blended with fine granular material. Laboratory and field tests will be required to establish their suitability.

CHAPTER IX

THJORSA RIVER DEVELOPMENT

GENERAL DESCRIPTION

The Thjorsa River and its main tributary, the Tungnaa, drain the area between the three glaciers: Hofsjokull to the north, Vatnajokull to the east, and Myrdalsjokull to the south, and a narrow belt south of the Hvita Basin.

The main Thjorsa flows from its source at Hofsjokull in a nearly straight southwesterly direction for about 230 kilometers to discharge into the North Atlantic Ocean east of Eyrarbakki. The Tungnaa rises from the ice fields of Vatnajokull and flows southwesterly until turning north and west along the Thjorsa lavas for its last 62 kilometers before joining the Thjorsa about 15 kilometers upstream from the mountain, Burfell. It receives some meltwater from the small glacier, Torfajokull, north of Myrdalsjokull. The Kaldakvisl River also rises at Vatnajokull, then follows in a parallel course to that of the Upper Thjorsa for about 75 kilometers to join the Tungnaa about 16 kilometers upstream from the latter's junction with the main Thjorsa. Lake Thorisvatn contributes its waters to the Kaldakvisl through the Thorisos, a short outlet river.

The tributaries which drain the area between the Hvita Basin to the west and the Thjorsa include the Kisa, Dalsa, and Fossa Rivers, listed in sequence from upstream. These are all relatively small rivers and their drainage areas total only about 625 square kilometers. There are a number of minor brooks which contribute their waters to the Thjorsa and to the tributaries mentioned above.

A plan of the Thjorsa Basin is included on Exhibit 3.

The Upper Thjorsa has a total fall of about 300 meters in 60 kilometers after it receives the waters of numerous glacial torrents in the wide and flat plain adjacent to Hofsjokull on the south and east and until it is joined by the Tungnaa at elevation 273 meters. One-hundred sixty meters of this fall are concentrated in the nine-kilometer long Thjorsa Gorge, near the center of the Upper Thjorsa, at the two great waterfalls, Glufurleitarfoss and Budarhalsfoss (Dynkur) and in associated rapids. Gentle grades prevail in the remainder of the Upper Thjorsa except for a drop of 15 meters at the waterfall, Hvanngiljafoss, eight kilometers upstream from Dynkur. The Kisa and the Dalsa enter the Thjorsa near Hvanngiljafoss. The gentle grade of the Thjorsa which begins at the foot of Glufurleitarfoss at elevation 305 meters continues for 17 kilometers beyond the mouth of the Tungnaa to the head of the waterfall, Trollkonufoss , east of Burfell, where the water surface is about 210 meters.

The second major concentrated drop on the Thjorsa occurs in a series of rapids and waterfalls as the River passes around the southerly end of Burfell. The fall totals nearly 90 meters in a River distance of seven kilometers. The Thjorsa resumes a relatively gentle gradient about one kilometer upstream from the mouth of the Fossa and on the west side of Burfell, which extends for 50 kilometers to the head of the Urridafoss Gorge. The total fall of 75 meters includes drops of 15 meters at the Skard Rapids and seven meters at the waterfall, Budafoss, both near the center of the reach.

The third major concentrated drop on the Thjorsa amounts to 33 meters as the River passes through the three-kilometer long Urridafoss Gorge, which includes the waterfall of that name. Beyond Urridafoss the fall amounts to only eleven meters in the remaining 18 kilometers to the ocean.

The profile of the Tungnaa River may be divided into three reaches based on position and relative gradient. The uppermost 80-kilometer long reach from near Vatnajokull to the Bjallar waterfall has a drop of about 140 meters on a nearly uniform gradient. The intermediate reach from Bjallar to near the mouth of the Kaldakvisl has a drop of about 240 meters as the Tungnaa flows for 30 kilometers along the margin of the Thjorsa lavas. This high gradient reach is characterized by falls and rapids concentrated at Bjallar, Tungnaarkrokur, and Hrauneyjafoss, each separated from the other by short stretches wherein the flow is at moderate gradient. The comparatively flat lower section extends from the Kaldakvisl junction, at elevation 321 meters, for 16 kilometers to the Thjorsa at elevation 273 meters, a drop of 48 meters on a nearly uniform grade.

Lake Langisjor, which drains easterly to the Skafta River, is located southwest of Vatnajokull in a long depression which parallels the Upper Tungnaa at a distance of about eight kilometers to the southeast. Its diversion from the river basin next easterly from the Thjorsa into the Tungnaa via the Lonakvisl may be feasible as is discussed in Chapter XVI.

Lake Thorisvatn, 70 square kilometers in area, presents a major seasonal storage potential. It is located favorably at elevation 571 meters between the Kaldakvisl and the Upper Tungnaa. Thorisvatn drains via the six-kilometer long Thorisos River to the Kaldakvisl. Upstream of the Thorisos confluence, the Kaldakvisl has a moderate and nearly uniform gradient. The fall downstream for 30 kilometers to its confluence with the Tungnaa amounts to 220 meters.

The important characteristic of the Fossa River is the near vertical drop of 220 meters at the waterfall, Haifoss, followed by an additional fall of nearly 100 meters in the rapids extending for five kilometers immediately downstream therefrom. The Fossa parallels the Thjorsa north of Burfell. The glacial basin, Fossolduver, upstream of Haifoss, may provide a small storage reservoir.

STREAMFLOW

The streamflow of the several segments of the Thjorsa River is affected by a number of factors which may not be the same for each segment. These include the glaciers, differences in precipitation, and bedrock permeability relationships. The effects of the former two factors are the consequences of elevation, primarily. The Hreppar rocks which dominate the area to the northwest of a line from Burfell and extending up the alignment of the Kaldakvisl, approximately, tend to be impermeable and the precipitation enters the streams as direct surface runoff regulated in some degree by small natural lakes. The remainder of the Thjorsa Basin consists principally of highly permeable Palagonite and post-glacial lavas and pyroclastics, all of which serve as important ground-water reservoirs to regulate the streamflows.

The only long-term (twelve-year) discharge record for the Thjorsa River is at Urridafoss, not far from the ocean. Several other gages have been installed upstream during the past two years, which is much too short a period to produce dependable records. Spot discharge measurements have also been made at various points within the Basin. Discharge values hereinafter referred to for locations other than Urridafoss are based almost entirely on correlation studies accomplished by the SEA[9].

The Upper Thjorsa begins as a glacial river, but its streamflow becomes modified progressively downstream from Nordlingaalda to the mouth of the Tungnaa by inflow from the tributaries which are all of the draga type. These two influences produce a pronounced variation from high summer to low winter flows. The estimated monthly average flow at Nordlingaalda reduces from 200 kl/s in July to 45 kl/s in January. The relative proportion is only slightly less proceeding downstream.

The Tungnaa River upstream from its confluence with the Kaldakvisl drains an area composed almost entirely of the three permeable rock types referred to above. It receives some meltwater from Vatnajokull and from Torfajokull. The streamflow of this portion of the Tungnaa is, accordingly, rather uniform. The estimated monthly average discharge at Hrauneyjafoss is 170 and 75 kl/s in June and January, respectively. The estimated average annual discharge is 107 kl/s.

Lake Langisjor can be considered as entirely glacial with practically no winter inflow.

The course of the Kaldakvisl River, and that of the Tungnaa downstream, tends to represent the boundary between the impermeable rocks to the northwest and the permeable rocks to the southeast, each with their different runoff characteristics. It receives some meltwater from Vatnajokull. Thorisvatn, which is almost entirely fed from underground sources and which has a nearly uniform surface outflow averaging about 14 kl/s, provides some degree of regulation to the flow of the Kaldakvisl downstream from the Thorisos. The aggregate effect of these influences is that the flow of the Kaldakvisl is only slightly less uniform than that of the Tungnaa above their junction, while the average flow of the former is about 65 percent of that of the latter.

The estimated average flow of the Thjorsa immediately downstream from its confluence with the Tungnaa, where the total drainage area is about 6300 square kilometers, is 334 kl/s. Approximately 60 percent of this yield is contributed by the Tungnaa and the remainder by the Upper Thjorsa. The monthly average flow in January is estimated at 213 kl/s.

Additional surface runoff and groundwater is received by the Thjorsa between the Tungnaa and Urridafoss, where the estimated average discharge is 377 kl/s from a total drainage area of 7200 square kilometers. The Fossa, basically a draga river, contributes an annual average of about 10 kl/s. Most of the remaining intervening drainage area consists of the permeable Thjorsa lavas.

The Thjorsa River at Urridafoss has nearly the same average flow as the Hvita River at Selfoss, but is somewhat more variable. The comparable monthly average flows are 246 and 399 kl/s in January, and 543 and 380 kl/s in July, both respectively.

POTENTIAL POWER DEVELOPMENT

The Thjorsa River and its tributaries have a large hydroelectric power potential, with a number of possible projects. The possible storage and power development is discussed by individual project or group of projects in Chapter X to XVIII, inclusive. The location of potential projects is shown in plan on Exhibit 3 and in profile on Exhibit 4. Again the general arrangement of each project (or group of several projects) as shown on the two Exhibits is intended to be illustrative only, and is not intended to present our specific recommendations for the development of each. The adopted layout for each can, in general, be established only after much further detailed investigation and study. The required investigations and alternatives to be studied are suggested or recommended by us in the specific Chapters referred to above. The arrangement shown on the two Exhibits presents our present opinion, based principally on judgment, on what may be near the optimum development for each proposed project. Pertinent data with respect to each such Project is shown on Exhibit 5.

The power and energy production of the overall development of the Thjorsa River Basin, as shown on Exhibits 3 and 4, has been estimated by us. The estimated average annual energy production is about 9600 million kilowatthours The estimated total ultimate capacity installation would be about 1,900,000 kilowatts. Some additional power and energy may possibly be developed economically by smaller projects which we have not studied. These projects may be located on tributaries, or represented by low head developments on the main Rivers, and which do not now appear attractive on the basis of present information.

The provision of storage reservoirs, including cyclic storage, in the upper reaches of the Thjorsa Basin will be important to economic power production farther downstream. A major storage reservoir located on each main branch is desirable, ultimately. Total ultimate storage capacity on the Thjorsa should probably be not less than 5500 million cubic meters.

Much greater storage is needed on the Thjorsa than on the Hvita because of the greater flow variations, and, fortunately, sites for storage reservoirs are available on the Upper Thjorsa and Upper Tungnaa, and at Thorisvatn, Langisjor, Bjallar, Tungnaarkrokur, Burfell, and Fossolduver.

The dam for the storage reservoir on the Upper Thjorsa, discussed in Chapter XII, would be located near Nordlingaalda. A volume of about 1200 million cubic meters may be available to a reservoir level of 590 meters. At-site power development is not considered feasible. The dam foundations in that area are somewhat complex geologically and extensive investigations are required to determine the optimum development.

A suitable damsite for a storage project on the Upper Tungnaa may be revealed by more detailed investigations in the reach between Ljotipollur and Faxafit. A proposed site at Vatnaoldur is not now considered feasible. The development of storage on the Upper Tungnaa, including the possible diversion from the Skafta River to the Tungnaa of waters stored by a development at Lake Langisjor, is discussed in Chapter XVI.

The development of Lake Thorisvatn appears to be the most feasible major storage reservoir in the Thjorsa Basin. Diversion of the waters of the Kaldakvisl River would supplement greatly the natural inflow of Thorisvatn. A diversion dam or dams would be required on both the Kaldakvisl and the Thorisös. Cyclic storage amounting to about 1500 million cubic meters could be achieved by a 27-meter drawdown of the Lake below elevation 571 meters, and could amount to complete regulation of these waters. The several possible alternatives for returning the stored water to the Rivers is discussed in Chapter XI. They include power development with long tunnels to either the Kaldakvisl or the Tungnaa. However, the most feasible alternative appears to consist of a two-kilometer long tunnel extending to a Regulating Pool located in a natural basin south of Vatnsfell from where the water would be released without initial power development through a secondary control structure to enter the Tungnaa River at the upper end of the proposed Tungnaarkrokur Reservoir. Power development downstream on the Tungnaa would be about equal in head to that resulting from return of Thorisvatn waters to the Kaldakvisl.

The several other possible storage reservoirs are associated with power developments and are relatively small. They are discussed with each proposed power project.

The stored water from Lake Thorisvatn as well as from any storage reservoir on the Upper Tungnaa could be utilized for power at the proposed Tungnaarkrokur, Hrauneyjafoss, and Lower Tungnaa Projects on the Tungnaa. These projects are discussed in Chapters XIII, XIV, and XV, respectively. Each of the former two Projects would develop a steep-gradient portion of the River by means of a fill dam and tunnel. Tungnaarkrokur could include about 200 million cubic meters of seasonal storage in its reservoir. The Lower Tungnaa Project would have its entire head created by a fill dam. It must be considered jointly with the Hrauneyjafoss Project to evolve the optimum development. The Lower Tungnaa Project, located nine kilometers upstream from the mouth of the Tungnaa, would receive the intervening inflow of the Kaldakvisl downstream from its diversion into Thorisvatn. The three proposed Projects could develop, overall, about 200 meters of gross head in 22 kilometers along the Tungnaa.

The only other proposed power project located in the Tungnaa-Kaldakvisl System which has been studied is the Bjallar Project, discussed in Chapter XVI. It could develop up to about 60 meters of gross head located upstream from the head of the Tungnaarkrokur Reservoir and thus would not receive stored water from Thorisvatn. This head would be developed by a fill dam and a tunnel. Seasonal storage amounting to about 200 million cubic meters might be possible. The Bjallar Project appears to be of relatively high cost.

The most favorable reach of the Upper Thjorsa River for power development is the steep gradient section of the nine-kilometer long Thjorsa Gorge which includes the waterfalls, Gljufurleitarfoss and Budarhalsfoss. About 185 meters of head between elevation 305 meters near the foot of Gljufurleitarfoss and elevation 490 meters at the foot of Hvanngiljafoss could be developed by a single project designated the Dynkur Project. This Project and other development alternatives are discussed in Chapter XII.

The Dynkur Project would include a dam located in a split-channel section one to three kilometers upstream of Dynkur, and a long tunnel.

The only other power project located on the Upper Thjorsa which appears worthy of study is the Hvanngiljafoss Project also discussed in Chapter XII. A dam located near the waterfall by that name could develop 25-30 meters of head above the elevation of the foot of the waterfall.

The largest potential power project on the Thjorsa River is located near the mountain, Burfell, and is discussed in Chapter XVII. Two development alternatives are possible. The Sultartangi alternative would divert the Thjorsa to the Fossa with a dam on the former a short distance downstream from the mouth of the Tungnaa, and a long tunnel. About 130 meters of gross head below elevation 290 meters would be developed. The second alternative, the Burfell Project, would include a fill dam on the Thjorsa near the head of the waterfall, Trollkonufoss, and a tunnel about 2.5 kilometers long extending through Burfell to rejoin the Thjorsa at elevation about 121 meters at a point about one kilometer upstream from the mouth of the Fossa. The reservoir level might extend from a minimum of about 235 meters to as high as 300 meters, the elevation of the tailwater at the Lower Tungnaa Project. Some seasonal storage may be provided in any reservoir higher than the minimum level.

The Haifoss Project, located at the waterfall of the same name on the Fossa River, is discussed in Chapter XVIII. It would be a moderately high head peaking plant. Between about 240 and 330 meters of head, depending on the alternative adopted, could be developed with a dam located near the head of the waterfall, and a tunnel. The reservoir in the Fossolduver Basin, created by the dam, could provide a seasonal storage of about 100 million cubic meters.

The proposed Skard Project might develop 55 meters of gross head in the 26 kilometers of river downstream from the tailwater of the Burfell Project to the foot of the waterfall, Budafoss. Alternatives for this development are discussed in Chapter XVIII. The fall of about 18 meters between Budafoss and the head of the reservoir for the proposed Urridafoss Project is not considered feasible of power development.

The Urridafoss Project is the lowermost proposed power project on the Thjorsa River. About 35 meters of head could be developed where the Thjorsa passes through the Urridafoss Gorge. The remaining eleven meters of fall extending on to the ocean is not considered feasible of development. Several alternatives for the development of the Urridafoss Project are discussed in Chapter X. Diversion of the Hvita to the Thjorsa at a point a short distance upstream of the Urridafoss Gorge is a possibility.

The geologic setting of most of the proposed projects on the Thjorsa Basin is somewhat complex. All sites beginning with Urridafoss on the Thjorsa and extending up that River and on up the Tungnaa as far as Bjallar have the permeable Thjorsa lavas making up one abutment of each.

These lavas also complicate the foundations for diversion dams on the Kaldakvisl. The permeable Palagonite Formation forms the other abutment at the three uppermost proposed power sites on the Tungnaa. This same Formation would be encountered at any storage site, including Langisjor, on the Upper Tungnaa, and the proposed outlet from Thorisvatn. Highly permeable pyroclastic materials may be associated with a proposed storage dam on the Upper Tungnaa. Rhyolite, a frequently dangerous tunneling rock, is associated with the Haifoss Project and the Sultartangi Project. The foundations for a storage project on the Upper Thjorsa contain permeable beds of glacial-fluvial material. Projects located in the Thjorsa Gorge or a short distance upstream therefrom appear to be the only ones in the Thjorsa Basin where permeable rocks may not be encountered in the foundations.

We do not believe, however, that any of the proposed Projects in the Thjorsa Basin will involve foundation problems of a truly unusual and excessively serious nature. The problems which will certainly be encountered in design and construction have been met in similar fashion at completed projects elsewhere, and successfully solved. Extensive geologic studies and foundation explorations will be required at each Project, and they will be time consuming.

Deposits of natural construction materials for each Project are believed to be adequate as to quantity, quality, and reasonable haul distance, with the possible exception of the Projects on the Upper Tungnaa where the haul distance for some or all materials may be rather great. The design of each individual Project must reflect the availability and suitability of the nearest natural construction materials.

CHAPTER X

URRIDAFOSS PROJECT

GENERAL TOPOGRAPHY AND GEOLOGY

The Urridafoss Project would develop about 35 meters of fall where the Thjorsa River forms a series of rapids and waterfalls before it widens to a broad deltaic river on the coastal plain about 18 kilometers from the ocean. The rapids are contained in a narrow gorge which commences at Heidartangi one kilometer upstream of the Thjorsa Bridge, and terminates one kilometer downstream of the major waterfall, Urridafoss. The length of the gorge is about 3.5 kilometers and has a natural fall of almost 33 meters. There is a wide and shallow section upstream of the gorge having a flat hydraulic gradient at elevation 44 meters, approximately. To the north and northwest, a low lava plain only a few meters above the river level extends between the Thjorsa and Hvita Rivers.

The geology of the site is described by Kjartansson[2] and Figures 22 through 25 of his Report show areal geology and sections. The right bank north of Urridafoss is formed by a Thjorsa lava flow, except at Sandholt, covering the alluvial sediments which were deposited on the bed-rock (Hreppar Series) when the area was still below sea level. The lava extends in some places into the present river channel, but mostly the edge follows the right bank of the river as far as the Urridafoss farm.

The Thjorsa lava and especially the alluvial deposits underlying it are permeable, as indicated by the springs issuing from the right wall of the gorge near the Thjorsa Bridge. A dam in the upstream part of the gorge will increase the hydraulic gradient and, unless measures are taken to tighten the foundations, the leakage will probably be excessive. There is no danger of piping through the lava, but in the underlying sediments some material may be washed out, creating open channels under the lava. At any selected damsite within the lava area, extensive exploration is required in order to determine the nature and extent of required foundation treatment.

Topography of the general area of the Project is available on scales of 1:50,000 and 1:100,000. Much of the Project area is covered by topography on a scale of 1:5,000 with a 2.5-meter contour interval.

A main highway passes through the Project area.

DEVELOPMENT ALTERNATIVES

The development of the Thjorsa River at Urridafoss for hydroelectric power was studied by Thoroddsen[1]. His studies included the four most logical damsites within the entire reach of the gorge, and which are shown on Exhibit 8. The head would be developed by tunnels or canals except for the lowermost Site IV located at tailwater. The planning studies should consider head development with a canal in connection with a dam at Site I. One suggested canal route would start at Heidarholt and convey the water south and west for 3.5 kilometers to a powerhouse located on the wide portion of the river below the gorge. This route is shown on Exhibit 8. The economics of the canal scheme depend to a great extent on the amount of rock excavation required, which information is not now available. Borings and probings will be required along any route studied. Another canal route farther to the south appears feasible and worthy of study, but the limits are slightly beyond the existing topography.

The previous studies do not establish definitely the most economical development as regards damsite location. Proceeding downstream from Site I, decreased water conductor lengths and cost are offset by increased height and cost of the dam. Additional factors therefore must be considered in the final selection of a project plan. A heightened watertable under the agricultural plain to the north and northwest will result with a dam at or below Site III and may limit headwater to below that for a dam located farther upstream which would continue to permit drainage. However, Site II may provide an only slightly less severe problem. Site II also may have a serious problem of reservoir leakage through and under the Thjorsa lava beyond the Sandholt, if no sealing measures were provided.

The problem of ice will have an important bearing on the selection of the damsite, and requires much further study. The problem at Urridafoss will be to maintain operation of the powerstation during periods of ice runs in the River when large quantities of frazil and sludge ice are transported downstream. In the present natural conditions the ice run is stopped by sheet ice at the wide section of the river downstream of the falls and starts accumulating upstream until practically the entire gorge is filled with ice. The amount of ice would be reduced if a large and deep reservoir could be created upstream of the gorge. Unfortunately, the topography does not permit a deep reservoir; one or two meters rise in normal water level upstream of Site I may be the maximum that can be permitted. Watertable studies and permeability studies will be required in order to establish the maximum normal reservoir surface upstream from the head of the gorge. This raising may result in velocities low enough to permit a solid ice cover on the lower portion of the reservoir under some of the more severe ice-producing conditions. Such an ice cover would reduce somewhat the formation of frazil ice and the quantities of sludge ice resulting from blowing snow. The design may also include provision for temporarily raising the reservoir level during severe ice conditions. This would encourage an ice cover on the reservoir but would flood, principally with ice, some agricultural lands which, however, may not be otherwise useful under the weather conditions at the time.

The dam at Site I, either directly or by virtue of a sheet-ice cover upstream, will under some conditions produce a temporary ice jam in the river and consequent increased water levels. The relatively great width of the reservoir should limit this increase to only a meter or two and may not be at all serious with respect to reservoir damage. A temporary partial or complete blockage at the intake could occur under the most severe conditions, but this may well be true to nearly an equal extent for any selected damsite. In addition and with a dam downstream from Site I, blockage could occur at or near the head of the gorge where the cross-section is narrow and shallow, especially under conditions of ice cover within the gorge.

A dam located downstream at Sites II, III, or IV would have the generally recognized advantage with respect to ice problems of a possible deeper elevation for the intake. This depth could be greater proceeding downstream.

A portion of the reservoir would be confined within the narrow limits of the gorge for each of the lower three potential damsites. The associated reservoir levels would probably not result in lowered velocities adequate to assure an ice cover on that portion of the reservoir under most frost conditions except possibly for a portion of the reservoir extending a short distance upstream from the dam. An ice cover near the head of the gorge would be rare. Under these circumstances, there is a strong possibility that an ice jam beginning at the dam or not far upstream would be a frequent occurrence. Such a jam could raise water levels several meters and produce flooding on the lava plain with possibly some bypassing of a portion of the flow across low ground and around the structures.

The final selection of the dam location can properly be made only after considerable further study, particularly with reference to the most feasible solution to the ice problem. The most advanced of design features can be expected only to reduce the effects of the ice conditions. Power-plants have been constructed in Europe and northern North America on rivers which are subject to sever ice runs similar to those on the Thjorsa. No proposed development, otherwise attractive, has to our knowledge been abandoned because of the ice problem. Design features and their relative success which have been incorporated in projects where severe ice problems exist should be studied in detail with a view to possible utilization at Urridafoss as well as at most of the other proposed projects in Iceland.

At the present time, we consider that Site I may be the most desirable damsite, with Site II the next most desirable alternative.

HVITA DIVERSION

The feasibility of diverting power flows from the Hvita to the Thjorsa for utilization through the Urridafoss Project should be studied further. This could involve a gated diversion structure on the Hvita and an open canal between the two Rivers, probably with a control structure at the head end. Hvita flood flows would continute to be passed on that River. This diversion would eliminate the Hestvatn Project and probably render the Selfoss Project infeasible. The Hvita flow could be utilized through a greater head with enhanced power and energy production. Some economies may also result with the single large powerplant at Urridafoss.

The most economical canal route involving adequate fall would probably be from the Hvita near the south end of Hestfjall to the Thjorsa near Vordusker, a distance of about four kilometers. The spillway diversion structure on the Hvita would be substantially the same structurally and hydraulically as proposed for the Hestvatn Project in Chapter V. Hydraulic studies would be required to establish the design capacity of the canal. The control structure and spillway should be designed to prevent Hvita ice entering the canal insofar as feasible. Velocities in the canal should be such as to encourage a sheet ice cover under at least the more severe frost conditions. Snow fences to reduce the amount of blowing snow entering the canal would be feasible.

Hydraulic relationships through the canal would reduce seriously the value of pondage in the Hvita reservoir upstream of the diversion dam, but pondage on the Thjorsa may be adequate for daily regulation of the resulting much larger Urridafoss Project.

Field investigations will be required if the planning studies establish the feasibility of the Hvita diversion. Those required for the Hvita dam and reservoir will be substantially identical with that for the corresponding features of the Hestvatn Project, but extended downstream to beyond its spillway location. Topography, drilling, and groundwater table investigations will be required along the selected canal route. Permeability studies of the Thjorsa lava and underlying alluvial material and bedrock along the canal route would be of special importance as a part of the drilling program.

The previously proposed diversion of the Hvita to the Thjorsa via the Stora-Laxa is not considered feasible.

SPILLWAY AND RESERVOIR

The operation of the reservoir on the Thjorsa will control the design of the spillway structure. This operation will be such as not to increase flooding hazards on the lava plain to the north, or seriously affect, for all lesser flow conditions, groundwater levels or drainage problems within that plain. The reservoir would be retained within the existing river channel and to the maximum levels which would fulfill the above requirements, except during large floods which would extend beyond the channel naturally. The operation would not increase levels during such floods.

A detailed groundwater investigation will be required throughout a large area of the lava plain to the north and northwest. Adequate observations together with simultaneous readings of stage gages along the Thjorsa will be required to establish the relationships between natural groundwater tables and river levels. The results should permit a reasonable determination to be made between future reservoir and resulting groundwater levels. Detailed mapping related to these studies will establish the areas which can economically be more or less permanently flooded.

The relation of reservoir levels to stage can, for planning and design purposes, be established by computed backwater curves.

With respect to a spillway at Site I, the principal hydraulic requirement in the design in order to fulfill the above reservoir requirements is the maintenance of hydraulic efficiency substantially equal to that of the reach of the natural river which the structure replaces. It will thus be necessary to maintain a clear opening in the spillway approximately equal to the natural river section and for nearly the full range of flows. Critical flow conditions through the structure during high-flow, fully-open conditions must be prevented.

The spillway structure at Site I in order to fulfill these requirements will consist essentially of a low concrete sill surmounted by piers and gates. Tainter gates or fish-belly flap gates should be the most economical type. If tainter gates are selected, one or more should be designed to recess slightly in order to pass ice and debris over the top without excess loss of water for power. This feature would also be appropriate for a spillway at any of the downstream locations, or even elsewhere in Iceland where the spillway is associated with a power intake.

The spillway at each of the three feasible downstream locations will involve a design to fulfill the above reservoir requirements. This can be accomplished with a conventional gated ogee spillway located across the river channel.

Hydraulic model studies of the spillway finally selected will be required to verify the design, including the design of the energy dissipator. Basic hydraulic and topographic data for the construction and calibration of the model will be required, most of which can be advantageously obtained at the time of field studies required for planning purposes.

INTAKE

A principal requirement in the design of the intake structure is the maximum feasible reduction in ice problems. Except for possible head development by canal, the intake structure will most likely be associated with the spillway. An alignment nearly normal to the spillway should be achieved. A skimmer wall upstream of the main intake appears desirable. The depth of the intake should approach the maximum feasible. Air bubbler systems may be desirable. The trashracks should be easily and quickly removable, provided with electric heating, and positioned entirely below water levels. An adjacent ice and silt sluice should be provided in the spillway. Details of design against ice problems should be accomplished only after a comprehensive study of designs utilized elsewhere, with particular emphasis on the history of performance. A skimmer wall at the head end of any canal may be worthwhile.

HEADRACE CANALS

The design proportions of a headrace canal would be established as a result of detailed studies. Design velocities should be such as to encourage creation and maintenance of an ice cover, at least during severe frost conditions. Any bedrock encountered along the canal route would be Hreppar and would be sound enough to permit steep side-slopes. The elevation of the bedrock surface would be established by probings and borings. The overburden material would need to be sampled and tested in order to establish safe design side-slopes. Snow fences parallel with the alignment would be desirable. The downstream portion of a canal route father to the south than shown on Exhibit 8 may consist principally of a low-cost enclosure dike on the low south side.

POWERHOUSE AND TUNNELS

Power developments at damsites I and II require tunneling unless the canal alternatives are found to be more economical. Large rock excavations are also required for the powerhouse and surge tanks (if required) located either underground or in deep open cuts. Because the Hreppar Formation in this part of Iceland generally consists of sound rock, it is probable that conditions for tunneling in the south bank will be favorable. But it is entirely possible that underground powerhouse excavation or a tunnel may encounter sedimentary strata or a Palagonite breccia sheet so weak structurally as to call for special construction procedures and a permanent lining, or so permeable as to give serious water problems, perhaps requiring extensive grouting. The first stage of the investigation should consist of mapping of individual flows outcropping in the vicinity of the tunnel, to be followed by diamond drilling at 500-meter intervals along tunnel routes, with water pressure testing at flow contacts and other changes in lithology.

The immediate aim of the drilling would be to work out the detailed stratigraphy of the rocks at the tunnel level. This can be readily accomplished on the basis of study of the core from the 500-meter holes if there happens to be distinctive sedimentary layers in the flow sequence, or if individual flows are identifiable on the basis of lithology, thickness, nature of the flow contacts, or other properties. Cross-checking between the drill core and exposures of the flows in the nearby gorge walls should be helpful. If obvious stratigraphic guides are lacking, closer-spaced drilling will be required. The point is that a special effort is justified because a knowledge of the stratigraphy is the only positive basis for determining, from the drill hole data, what rock conditions are to be anticipated between the drill holes. For example, if the individual flows are not identified, water pressure tests at interflow contacts represent only a random sampling of conditions that may be encountered, but if a given contact is consistently tight or permeable in a representative number of holes, it is reasonable to assume that it will have the same property throughout the drilled area, and it may be possible to locate the power structures accordingly. Similarly, it is in the highest degree unlikely that faults which may cross the tunnel route will be cut by drill holes, but if the stratigraphy is known the presence and general location of faults of any considerable vertical displacement will be evident, and the faulted areas can be investigated further if this seems advisable.

It is unlikely that any preglacial valley, filled with superficial material, will be intersected by the tunnel. The diamond drill holes will provide data on the form of the rock surface, and there are outcrops of basalt along some parts of the tunnel route. After these data are assembled it may be advisable to probe for the rock surface in covered segments that might conceal a buried valley.

The type of powerhouse would be established by detailed planning studies. While Exhibit 8 indicates a surface powerhouse with Site I, an underground powerstation, probably of the trench type, with either a headrace or tailrace tunnel, is almost certainly feasible and should be studied. The fact that a surface powerhouse in the lower gorge would almost certainly need to be designed against high tailwater from possible ice jams would act in favor of the basically underground design.

The initial construction would include provisions for adding such additional generating units as the planning studies may show to be justified. These provisions might take the form of either partial initial construction such as water conductors sized for future requirements, or a design lay-out suitable for substantially separate future enlargement.

The turbines should be of the automatically adjustable blade propellor (Kaplan) type. However, the planning studies should investigate the comparative economies of fixed-blade propellor turbines inasmuch as the head is not likely to vary appreciably with variations in river flow. Provisions for heating either the wheel pits or the turbines to remove or prevent the build-up of ice thereon should be made. The planning studies will establish the economic number of generating units, both initially and ultimately.

WATER SUPPLY, POWER, AND ENERGY

Estimates of discharge of the Thjorsa River at Urridafoss are included in the SEA Report[9]. These flows are tabulated on an average monthly basis and plotted as a continuous hydrograph on an average weekly basis for the period April 1946 to August 1958, inclusive. A duration curve based on these flows is included. The gage is located at the Thjorsa Bridge towards the upper end of the gorge.

Significant data from these records are as follows:

Average discharge - 11 years	377 kl/s
Average discharge - minimum year	293 kl/s
Minimum monthly discharge	106 kl/s
Minimum weekly discharge	84 kl/s
95% discharge	136 kl/s
50% discharge	320 kl/s
39% discharge	377 kl/s

System Operation Studies which would consider the Urridafoss Project as an addition to the then existing system will be required in order to establish the initial capacity of the Project. They would be extended to establish the ultimate capacity with the Thjorsa nearly fully developed for power. This would consider the effect of storage at potential sites upstream on the Thjorsa and its tributaries.

Urridafoss may initially be primarily an energy plant operating at relatively high annual capacity factor, but in the future may become more of a peaking plant if hydraulic studies show that adequate pondage is available.

We believe that the initial flow capacity of the Project should be about equal to the mean annual flow, and divided between either two or three units. Provision should be made for one or possibly two future units of like size. This initial capacity would amount to about 100,000 kilowatts. The average gross annual energy production would amount to about 740 million kilowatt hours, which would reduce to about 620 million kilowatt hours in the minimum year of record (1950-51). Corresponding annual capacity factors assuming all energy utilized on load would be about 85% and 70%, respectively.

These estimated energy values are based on the flows of record, which is relatively short-term and may not be truly representative of long-term conditions. Drier years than 1950-51 can certainly be expected.

Comparison with longer-term meteorological and hydrological records may give some clue as regards these relationships.

The unregulated run-of-river energy production from the Urridafoss Project may not be fully utilizable to load during initial years of operation. Winter flows average about three-fourths those for the year and drop to about one-fourth the average. High flows are usually consistent for the months from May through August. Regulation by a storage reservoir upstream on the Thjorsa or its tributaries is rather vital to improving the quality of the energy from Urridafoss. Detailed Project and power studies may show that such a reservoir can be justified economically at the time or shortly after Urridafoss is constructed even without another upstream powerplant to utilize the storage.

FIELD INVESTIGATIONS

Reservoir

River cross-sections and associated stage-discharge records at intervals of about one kilometer through the gorge and two kilometers upstream of the gorge will be required as the basis for reservoir backwater studies. These measurements should extend from below the lowest proposed damsite and upstream as far as Reykjaheid.

The existing 1:5,000 scale topography should be extended to the north and northwest by about one kilometer on the lava plain. Contours at one-half meter intervals below elevation 50 should be accomplished for this entire mapped area of the plain. An eastward extension of this topography up to elevation 50 may also be required. In addition, the accuracy of the existing topography should be carefully checked.

The survey should locate and establish groundwater elevation gages on roughly a one-half kilometer grid through the mapped area of the lava plain north of the River. These can be located at "swallow" holes and other depressions which extend below the groundwater table and are numerous in the area. Adequate observations together with simultaneous reading of the stage gages along the Thjorsa will be required to establish the relationships between natural groundwater tables and river levels. These gages should be permanently observed until general relationships are established, but regular readings will not be required except during major rising and falling stages on the River.

The discharge of the springs near the Bridge should be measured, and at various River stages. This will permit correlation also with the groundwater table variation under the lava plain. If Site I is adopted for the spillway, the variations in flow during grouting operations and filling of the reservoir should be observed.

Spillway

Two cross-sections taken at each of the four proposed damsites should be adequate for initial planning purposes. This would be supplemented by detailed topography and soundings at the site ultimately selected. Diamond core drilling at each site is desirable, but probably not essential prior to final site selection. The selected site should be drilled and water pressure tested in detail. Eight holes in the riverbed section may be adequate. Two or more holes would be required in each abutment except at Site I, where additional drilling would be necessary beyond the right abutment. The Hreppar flows on the left abutments are considered to be generally watertight. The alluvial interbed under the Thjorsa lava beyond the right abutment at Site I is highly permeable and some form of grout curtain will probably be required. About five holes at not greater than 100-meter centers should be drilled in order to check the inference drawn from the surface geology and the springs discharging at the north wall of the gorge. It is unlikely, however, that any amount of drilling will give an answer to the question of how large the leakage will be because the leakage paths are irregular, and may not even be recognized from the cores. Pressure testing will give some indication of the permeability and should be carried out at regular intervals and at changes in lithology.

Detailed geology would be developed at the selected spillway site from the drilling, supplemented by surface mapping. The thickness and stratigraphy of individual flows and interbeds will be of most importance.

Power Features

The 1: 5,000 scale topography should be extended about one kilometer to the south with one-meter contours to include the route of a canal farther to the south than shown on Exhibit 8. The topography is otherwise adequate for planning purposes, but detailed topography will be required for design purposes at the site of any structures.

Probings and borings to establish bedrock elevations along canal routes would be required in the planning stage for comparative estimating purposes. Diamond core drilling of the bedrock would be required if a canal scheme is adopted. The overburden material would need to be sampled and tested to provide information for side-slope design.

The geology and subsurface investigations for underground structures has been discussed above. Diamond core drilling and water pressure testing will be required at the site of any powerhouse selected for design.

Tailwater gages should be established and rated at the location of any proposed tailtunnel outlet or surface powerhouse location.

CONSTRUCTION MATERIALS

Concrete aggregate would be the principal natural construction material required. Beach deposits along a nearby ancient shoreline at about elevation 100 meters would probably represent the most economical source for processing. One deposit of coarse aggregate was observed in a pit being mined for road fill and located at Krossholl about four kilometers to the east of the Project. Deposits of fine material were noted about three kilometers to the south of that pit. A geologic reconnaissance should be made of the shoreline deposits in the general area, followed by sampling and testing from the most promising deposits. Fine aggregate may exist in bars in the riverbed upstream of the gorge and this possible source should be investigated. Basalt from the Thjorsa lava or the Hreppar Series is doubtless suitable for manufactured aggregate as well as rock-fill material, if required. A quarry in the latter is located in the Project area at about two kilometers south of the Bridge. Tunnel spoil may also be suitable for processing. These bedrock sources should not need to be investigated in detail unless tests develop the shoreline material to be unsuitable. Suitable core material for any rockfill dam construction likely can be located in the immediate area, but was not specifically observed.

WATER TEMPERATURES

It would be desirable to have temperature records of the air and water during the winter months in reference to ice conditions. The water temperature should be measured to an accuracy of one hundredth of a degree Centigrade in the range between freezing and four degress. It may not be possible to make a quantitative estimate of the amount of ice carried by the river at any time, but a rough estimate should be made, based on visual inspection and the rate of accumulation in the gorge.

The data obtained from these observations may also be useful during the first few years of plant operation.

CHAPTER XI

THORISVATN STORAGE AND KALDAKVISL DIVERSION

GENERAL TOPOGRAPHY AND GEOLOGY

Lake Thorisvatn can be developed into a large storage reservoir for regulation of its own underground inflow and diverted inflow from the Kaldakvisl River. Stored waters can be released for firming the flow of the main Thjorsa River and possibly the lower three proposed projects on the Tungnaa River. Thorisvatn is the second largest natural lake in Iceland with 70 square kilometers of surface area at its normal level of 571 meters. It is conveniently located between the Tungnaa and its principal tributary, the Kaldakvisl. The Thorisvatn drains northerly to the Kaldakvisl via the Thorisos River, a relatively short, low-gradient outlet. A low saddle about five meters high at the southwest end of the Lake divides it from drainage to the Tungnaa. This divide tends to limit the increase in water levels in the Lake, and storage would be accomplished principally by drawndown below present levels. The Lake is otherwise surrounded by relatively high topography with steep slopes extending to below water level. Thorisvatn is over 100 meters deep over large areas. An undrained depression containing two small shallow unnamed lakes lies three kilometers to the south of Thorisvatn and is separated from it by the mountain, Vatnsfell. This depression is about three kilometers in length along its major north-south axis.

The Kaldakvisl River rises at the ice fields of Vatnajokull and flows southwesterly in a generally straight alignment to join the Tungnaa River below Hrauneyjafoss. It passes to the north and northwest of Thorisvatn at a distance of about four kilometers. Its grade north of Thorisvatn is such as to permit diversion with a dam of nominal height reversing the flow in the Thorisos and adding the flow of the Kaldakvisl to Thorisvatn.

The general geology of the Thorisvatn-Kaldakvisl Diversion area has been described by Kjartansson [2]. An extensive post-glacial lava flow is located to the east of Thorisvatn and the Thorisos and provides the source of most of the underground inflow into the Lake. Palagonite and other clastic rocks form the containing hills to the south and west; and, together with basalt (possibly of the Hreppar Series) and overlying moraine, the hills to the northwest. Six diamond driven holes were accomplished on the axis of a proposed dam across the Thorisos River and developed the general stratigraphy in that vicinity.

Topography on a scale of 1:20,000 with a contour interval of five meters is available for nearly the entire Project area. The area between the depression south of Thorisvatn and the Tungnaa is not covered by this topography, but we understand that the photography and the ground control thereof is complete so that mapping can be readily accomplished. The existing surveys include a hydrographic map of Thorisvatn with ten-meter contours.

DEVELOPMENT ALTERNATIVES

Kaldakvisl Diversion

A dam or dams will be required to raise the water level of the Kaldakvisl higher than the maximum level of Lake Thorisvatn in order to permit gravity diversion. Two alternatives for dams were presented by Thoroddsen[(1)] and Kjartansson[(2)]. They are designated the "Upper Site" and "Lower Site" on Exhibit 9. The Upper Site would consist of two dams, one on each of the two Rivers, Kaldakvisl and Thorisos. The Lower Site would involve a single dam crossing both Rivers about two kilometers upstream of their junction. The Kaldakvisl Dam of the Upper Site alternative would be located about four kilometers upstream, while its companion dam on the Thorisos would be about two kilometers upstream. We concur that these alternative damsites are the only ones worthy of further study. Further studies are required as a basis for selection between the two.

A fill type of dam is suggested for the Lower Site, but additional studies and investigations will be required to establish the exact type. A homogeneous type constructed either of silt and sand or of morainal material may be feasible. A composite type utilizing one or the other of the above materials for the upstream side and rockfill for the downstream side should be studied. However, a rockfull with impervious core (or concrete facing) is very likely to be the most economical. Studies should also include designs utilizing concrete and fill segments.

No serious foundation problems are expected at the Lower Site. The underlying bedrock is sound basalt or basalt breccia, resembling the Hreppar Series. A tongue of the post-glacial lava overlies the basalt between the two Rivers, but probably averages only a few meters in thickness. Unconsolidated alluvial and morainal material is interbedded between the two and is likely to be thin but highly permeable. A concrete curtain wall constructed in a trench excavated through to the basalt is suggested as a cutoff, but will need to be compared with the cost of treatment by grouting. Little if any grouting should be needed in the basalt. The moraine covering the bedrock on the left abutment should be suitable as the foundation for a fill dam and requires no treatment other than removal of surface weathering.

A spillway may not be required at either the Lower or Upper Site. The Thorisvatn storage should be able to receive any probable flood from the Kaldakvisl. However, a fuse-plug type of emergency spillway should be installed. The most logical location would be through the low divide at the southwest end of Thorisvatn, but alternative locations near the dam should be studied. Any discharge in the event of emergency rupture at the southwest end of the Lake will flow southwestward to discharge into the Tungnaa upstream of Tungnaarkrokur. There may be considerable erosion, but the risk is acceptable in view of the remote chance that it would ever happen. A concrete control sill would be required in order to limit the loss of storage in Thorisvatn resulting from such a rupture.

The Kaldakvisl Dam at the Upper Site may be either of rockfill or concrete construction, with the former likely the most economical. The foundations would be entirely in sound basalt requiring little or no grouting.

A rockfill dam is recommended for the Thorisos Dam at the Upper Site. Alternative types of fill dams as well as a dam containing concrete and fill segments may also be studied. The foundation conditions at the damsite as revealed by the six drill holes present more problems than at the other damsites. The principal problem is the permeability of the lava and particularly the upper portion of the moraine immediately beneath it, and which extends for a distance of about 500 meters east from the River. Treatment by grouting will be required, but may be difficult and expensive. The remainder of the moraine and the basalt and clastic rock underlying it can be considered adequately sound and should require relatively minor routine treatment, or none at all,

One or more smaller dikes may be required along the ridge between the two dams of the Upper Site, depending on the top elevation required for the overall structure. The basalt and overlying moraine should present no foundation problems with these low structures.

The interrelation to the damsites and to Thorisvatn of the grades of the two Rivers is shown on the profile of Exhibit 9. The present outlet of Thorisvatn at about elevation 570 meters will be a hydraulic control point for the diversion. The diversion dam (or dams) must be of the height as required by the maximum hydraulic gradient towards the control, and would be several meters higher than the maximum Lake level during diversion of the maximum probable flood. It is evident that increasing the normal maximum level of the Lake more than about one meter probably cannot be justified because of greater height and cost of the diversion dam.

The Kaldakvisl has a fairly steep gradient of about three meters per kilometer and, being a glacial river, carries considerable sediment and bedload. The samples taken by the SEA appear to verify this assumption.

Most of the bedload will deposit in the Kaldakvisl Reservoir upstream of the Thorisvatn control. The hydraulic gradient towards the control point will steepen in time and may produce the requirement of raising the dam, though some excess freeboard may be incorporated therein at the time of initial construction. The diversion dam, then, may need to be designed for ultimate raising, perhaps in more than one stage.

The Kaldakvisl will ultimately establish a gradient as a result of this sedimentation extending upstream from the control point and approximately parallel to its present grade. The time requirement to reach this condition cannot be reliably estimated but will likely be many years. Silting with respect to elevations would most certainly be quite rapid during the first few years after construction.

Diversion of the Kaldakvisl into Thorisvatn with a dam at the Lower Site would be upstream through the bed of the Thorisos and no excavation would be required. Dams at the Upper Site would require either a canal or an offsetting increase in dam height for this same purpose or both. The silting problem described above would preclude the use of a tunnel. One canal route is shown on Exhibit 9, but alternative alignments exist and should be studied. The grade and proportions of the canal versus increased dam height would require a related economic analysis.

Studies and investigations would be basic to the selection of the dam location between the two alternatives presented above. The volume for a fill dam at the Lower Site would be on the order of one million cubic meters and may be considerably greater than for the dams of the Upper Site. Foundation treatment is likely to be far more expensive at the Upper Site, and additional work is required for a canal to full size. A limitation on the diversion capacity above the design level through the canal would require wasting of flood waters (and energy), and a controlled spillway for this purpose. Future raising as required by sedimentation is likely to be more expensive at the Upper than at the Lower Site. It is our present opinion that the Lower Site is preferable, and possibly no more costly.

Thorisvatn Storage

Stored water from Thorisvatn may be released for power and energy production in two alternative directions: one westward into the Kaldakvisl and the other southward into the Tungnaa. Both alternatives have been studied by Thoroddsen [(1)] and designated the Thorisvatn and Vatnsfell Developments, respectively. A geologic reconnaissance of the general area with specific reference to several tunnel route alternatives for the westward diversion has been made by Kjartansson [(2)]. All of these plans involve long tunnels with associated underground power stations.

Thoroddsen's Thorisvatn Development would involve nearly twelve kilometers of headrace and tailrace tunnels for a gross head development of about 240 meters, maximum. Three alternative tunnel alignments are shown on his Drawing A-1679, Sheet 4; the most southerly is shown on Exhibit 10. The geologic stratigraphy is, according to Kjartansson [(2)], similar along all three routes. The headrace tunnel will be in Palagonite interspersed with basaltic rocks and under a moraine cover. The tailrace tunnel would be mostly in basalt. The tunnels would be below the watertable and water problems, locally serious, may be expected throughout. The headrace tunnel would require some support probably throughout, and concrete lining. Support and concrete lining may be required to some extent in the tailtunnel, and complete lining may be economic. We do not concur in the proposal to draw down Thorisvatn during driving of the headrace tunnel by means of a 2.5 kilometer long drain tunnel.

Thoroddsen's Vatnsfell Development (designated Long Tunnel Alternative on Exhibit 10) would include a 6100-meter long headrace tunnel and a 200-meter long tailrace tunnel. The intake would be in the Lake at the north end of Vatnsfell. Both tunnels would be in Palagonite and require concrete lining, with some support in places during driving. Some water problems during driving can be expected. Additional study is required with respect to possibly inadequate cover locally over the headrace tunnel. The tailrace would discharge into the Tungnaarkrokur Reservoir at elevation 500 meters. The entire gross head of 71 meters, maximum, between the two proposed reservoirs would thus be developed. The stored water would be utilized through the Tungnaarkrokur and Hrauneyjafoss Projects on the Tungnaa and thus overall head utilization would be comparable with that for the westward diversion.

We propose for detailed study another plan of development alternative to the two plans described above. Our plan would involve the diversion of stored water from Thorisvatn through Vatnsfell by a controlled tunnel, or canal and tunnel, about 2.5 kilometers long into the depression to the south which would form a Reregulating Pool. A concrete control structure located in the low saddle at the southwest end of the Reregulating Pool would release the water through a canal to the Tungnaarkrokur Reservoir. The canal would be concrete-lined in the upstream steep section to prevent erosion. Power features would not be included initially, but provision for developing for power the 40 meters of gross head between the Tungnaarkrokur reservoir at elevation 500 and the Reregulating Pool at about elevation 540 may be desirable. This plan of development is also shown on Exhibit 10.

The diversion tunnel would pass through Palagonite in Vatnsfell. Surface exposures indicate that this rock at tunnel grade may be mostly basalt breccia of relatively good quality. Concrete lining would be required, but little support should be necessary. Some water problems can be expected, especially near the entrance into the Lake.

The proposed elevation for the intake is about 540 meters or about 31 meters below the normal Lake level. The construction to accomplish entry into the Lake will require special study. Caisson construction may be required if the control structure is located at the upstream end of the tunnel. Alternatively, a vertical control structure shaft may be excavated from the surface (within a cofferdam if located in the Lake), and the last few meters of tunnel drilled from the inside and opened out by a single blast. Good, watertight rock, possibly made so by grouting, would be required to assure feasibility of the latter plan.

The Lake entry problem may be greatly reduced by open canal excavation along the general alignment shown on Exhibit 10. A gated control structure would be located in the canal. The length of the tunnel would be reduced to about one kilometer; however, the overall scheme is likely to be more expensive than the tunnel-only plan.

The Reregulating Pool would be located in Palagonite. The permeable nature of this rock will result in some, probably minor, seepage. However, this seepage would enter the Tungnaarkrokur Reservoir and thus not be lost for energy production downstream. The Palagonite is doubtless suitable as a foundation rock for the control structure.

Each of the three alternatives outlined above for developing Thorisvatn storage should be studied in detail on a comparable basis. The utilization to be made initially and ultimately of this storage will have an important bearing on the sizing of all structures and the overall economics of each alternative of the Project, and must be the subject of System Operation Studies. Cost comparisons with other storage possibilities on the Upper Thjorsa and Upper Tungnaa will also have an important influence on the selection.

The principal value of the Thorisvatn Project (including the Kaldakvisl Diversion) is its utilization for storage rather than for head and at-site power. This storage would be utilized, in coordination with other storages, for optimum power and energy generation at-site and at downstream powerplants, all integrated within the overall Southwest Iceland Power Supply System. The storage releases under any level of system development would be decidedly non-uniform. They would be confined for the most part to a few weeks (not necessarily consecutive) of the year if Thorisvatn is constructed relatively early in the expansion program. The addition of other system storage may change the release pattern only slightly, except possibly in point of time. Further, Thorisvatn would almost certainly, and at all levels of system development, be utilized as a cyclical reservoir, with storage held in reserve for use in drier years.

At-site power development, then, would have a very low annual capacity factor with a relatively large and costly installation in relation to the energy produced. The power and energy may not always be fully utilizable to load. The System Operation Studies and analyses based thereon are almost certain to show that at-site power development at Thorisvatn could not be justified economically, except possibly late in the overall power development program, many years hence. Accordingly, the most economical initial development for storage only would be of primary importance. It is our present opinion that the development alternative we proposed above of diverting Thorisvatn storage into the Reregulating Pool for release to the Tungnaa should be adopted as the basic general plan. This development may not include initially the diversion of the Kaldakvisl. In this case a temporary closure dike at the head of the Thorisos may be beneficial. However, with this alternative, all initial construction should provide for the ultimate diversion of the Kaldakvisl. Overdrawing of Thorisvatn storage in excess of natural inflow and in anticipation of ultimate replacement from the Kaldakvisl may be economical. This may amount to a total of 25 average annual kiloliters per second (including inflow) for as long as five years.

The inclusion of Kaldakvisl waters into the Thorisvatn storage can result in nearly complete regulation of flow on the Tungnaa except for major flood periods. Seasonal storage in the Tungnaarkrokur Reservoir would be from these flood waters. Thus these two Projects may possibly render uneconomic, for many years, a major storage reservoir on the Upper Tungnaa, which would doubtless be required if Thorisvatn waters were returned to the Kaldakvisl.

The water added to the Tungnaa from Thorisvatn would result in increased justifiable capacity at the proposed Tungnaarkrokur and Hrauneyjafoss Projects over that required for Tungnaa waters alone. This would be relatively low-cost incremental capacity, inasmuch as the common features of the Projects, such as dams and spillways, would be required more or less regardless thereof. It is our present opinion that basic planning of these two Tungnaa Projects should include consideration of the added water and regulation from Thorisvatn. The regulation from Thorisvatn will also have an important bearing on the plan of development at other downstream plants on the Tungnaa and Thjorsa. For example, development at Urridafoss may justify Thorisvatn construction rather early in the life thereof and possibly in advance of any capacity development between the two.

WATER SUPPLY, POWER, AND ENERGY

The actual inflow into Lake Thorisvatn is unknown because of the underground nature of the source. Data with respect to estimated flows is presented in the Kjartansson Report[2]. The surface outflow into the Thorisos is fairly constant at about six kl/s. A continuous recording gage was established in February 1958 at the site of the proposed diversion dam on that River. The SEA Report[9] shows estimated average monthly flows at this gage location, and also gives an annual estimate of 14 kl/s. The increment above the Lake's surface outflow is accounted for presumably by intervening springs fed by seepage through the pervious lava dam at the north end of the Lake.

The entire flow measured at this point, or somewhat more, depending on the location of the diversion dam, could be saved for storage. Substantial leakage occurs through the Palagonite rocks to the west and reappears ultimately in the Kaldakvisl, the Utkvisl, the Blautakvisl, and in some other brooks. The total leakage in this direction has been estimated to be between seven and ten kl/s. This leakage to the west may be somewhat reduced during seasonal drawdown of the Lake, but would be increased by any rise in normal levels. Reduction of this leakage by grouting is not considered feasible.

Streamflow records on the Kaldakvisl are also somewhat meager. A continuous automatic stage recorder was established in April 1959 south of Saudafell and about nine kilometers upstream from the mouth of the Thorisos, but streamflow records are not available therefrom. The SEA Report gives an estimate of 33 kl/s for the average annual discharge at this point.

The average yield from the Kaldakvisl and Thorisvatn available for regulation may, then, be on the order of 45 to 50 kl/s. The assumed annual yield would thus be about 1600 million cubic meters. Full annual regulation of this volume usually requires about 75 percent of the annual yield or, in this case, about 1200 million cubic meters. However, in order to provide holdover storage for dry years, we recommend an allowance of about 1500 million cubic meters. The required maximum drawdown on the basis of the hydrographic survey of the Lake would be about 2.7 meters below elevation 571 meters. However, underground storage, particularly in the lava to the east, is likely to be substantial and actual operation may show that the required storage can be achieved with a lesser drawndown.

The gross at-site energy, if and when developed, would be dependent on the net head ultimately developed and the installed capacity. The energy increment at the aforementioned two plants on the Tungnaa is discussed in Chapters XIII and XIV. The energy increment at plants developed downstream from the mouth of the Kaldakvisl would be small; the principal benefit would result from the enhancement of nearly all energy from such plants with respect to load.

FIELD INVESTIGATIONS

Kaldakvisl Diversion

No additional topography appears to be required for planning purposes. Detailed topography on a scale of 1:1000 with one-meter contours in the vicinity of the dam or dams selected for construction will be required for design purposes. The same is true in the area of any canal selected for design, and below elevation 580 meters between the canal and the Lake.

Foundation investigations are required at the Lower Site. At least two diamond drill holes, carefully water-pressure tested, are required through the lava between the two Rivers and into the underlying basalt at least two meters. These should be accomplished prior to detailed planning. If the Lower Site is selected for design, additional borings at not greater than 100-meter centers generally along the axis for the entire length of the dam are required. Churn drill holes may be preferable to diamond drill holes where the dam would be founded on moraine. They may also prove preferable to diamond drill holes in the lava area. Permeability tests on all holes are of primary importance.

The drilling will permit the compilation of the geologic stratigraphy along the axis. No additional areal geologic mapping is required.

The stratigraphy at the Thorisos Dam of the Upper Site has been adequately developed by the previous drilling, but permeability information is lacking. A reasonable attempt should be made to recover the previous holes and subject them to water pressure tests. Four churn drill holes into the underlying basalt or clastic rock (Palagonite) should be drilled and subjected to thorough permeability tests during drilling. Two of these should be through the lava with an additional one each to either side thereof. These tests made prior to detailed planning will develop the need, if any, for additional similar investigations prior to design in the event the Site is selected for construction.

No foundation borings are required in advance of planning at the Kaldakvisl dam of the Upper Site. If selected for design, the investigations would be similar to those at the Lower Site.

Churn drilling through the moraine to establish bedrock elevations will be desirable along the canal route or routes at about 200-meter centers prior to planning. Permeability tests are not necessary.

Thorisvatn Storage

The existing 1:20,000-scale topography should be extended to include the area between the proposed Reregulating Pool and the Tungnaa River. This should provide adequate topographic information for planning purposes.

More detailed topography will be required for design purposes. The area of the Reregulating Pool control structure and associated canal should be mapped in a scale of 1:2,000 with one-meter contours. The downstream adit of the tunnels should be similarly mapped. Detailed soundings adequate to produce maps on a scale of 1:1000 with one-meter contours will be required of the Lake bottom along the canal route or to the north of Vatnsfell where the diversion tunnel would enter the Lake, depending upon which alternative was selected for design.

Foundation investigations will be required at the site of all structures. These should probably consist of churn drill holes except at the Vatnsfell diversion tunnel upstream adit where diamond drilling would be required. Permeability tests would be made during drilling. Borings will be required at about 100-meter centers along the Reregulating Pool Outlet canal route where unlined and at closer intervals where lined. At least six holes will be required at the site of the control structure. At least two holes should be drilled at the selected downstream adit of the tunnel. If the canal alternative is selected for the diversion from Thorisvatn, borings should be made at about 100-meter centers, with additional holes at the selected site of the control structure. Thorough diamond drilling, perhaps at ten-meter centers or closer, would be required at the site of the upstream adit of the diversion tunnel from the Lake, and between that point and the shore. The area of the control structure if not included therein will also require close-spaced drilling. Water pressure tests of these holes will be necessary. The entire area of the structures for the Thorisvatn Project is in Palagonite and areal geology is not necessary. The drilling may possibly permit some stratigraphic correlation locally.

CONSTRUCTION MATERIALS

Inasmuch as fill type of construction is envisioned for the Kaldakvisl Diversion Dam or dams, a thorough investigation for natural construction materials is necessary. The morainal material may be suitable for rolled-fill construction. Tests should be made to determine if it can be satisfactorily excavated, broken down, and compacted into a suitably impervious fill material; or satisfactorily blended with fine granular material as an alternative. Such tests are suggested for the design stage only. A deposit of fine sand and silt was observed within and adjacent to the River immediately downstream from the

Lower Site. A smaller deposit was observed immediately upstream from the Kaldakvisl dam of the Upper Site. These deposits should be explored as to extent, then sampled and tested as to suitability for rolled-fill and core construction, as well as for concrete fine aggregate.

The lava appears to be the most suitable material for rockfill shell construction. The older basalt may also be suitable, although the solifluction products from it revealed a platy tendency and, accordingly, it may not break to produce a suitable product.

The lava may be the only suitable source in the immediate vicinity of the dams for the manufacture of coarse aggregate for concrete. No surface gravel deposits were observed, though an esker in that vicinity is a remote possibility worthy of reconnaissance. Sand and gravel was observed in the shallow southwest portion of Thorisvatn. This potential aggregate source should be investigated prior to design. Unless this source is favorable, concrete aggregate for the structures of the Thorisvatn Storage Project may present somewhat of a problem. The Palagonite generally is not considered suitable as a source for manufactured aggregate. However, the basalt breccia phases in the lower levels of Vatnsfell may be suitable and should be investigated. Tunnel spoil from the Vatnsfell tunnel may, therefore, be satisfactory for this purpose.

CHAPTER XII

UPPER THJORSA DEVELOPMENT

GENERAL TOPOGRAPHY AND GEOLOGY

The Upper Thjorsa, as herein designated consists of the portion of the River upstream from its confluence with the Tungnaa to its source in glacial torrents of the Hofsjokull. This segment consists of three sections that are sharply contrasted from the standpoint of hydroelectric power development, as follows:

1. The Lower Section. A low gradient reach extending about 20 kilometers upstream from the mouths of the Tungnaa distributaries through which the Thjorsa braids on a wide valley floor formed by filling of a lake dammed by the Thjorsa lavas.

2. The Thjorsa Gorge Section. A post-glacial gorge with about 162 meters of fall in the nine kilometers upstream from the Lower Section. It is characterized by two great waterfalls: Gljufurleitarfoss with about 30 meters drop and Budarhalsfoss (Dynkur) with about 65 meters of drop. The remainder of the fall is represented by steep rapids.

3. The Upper Section. An upper open valley reach, starting about three kilometers upstream from Dynkur, with about 100 meters of fall in about 32 kilometers up to the area of the glacial streams issuing from Hofsjokull. Through this reach the Thjorsa has in most places cut less than about ten meters below a glaciated surface of low rolling relief. Our field reconnaissance covered this latter Section. This Section presents possibilities of development for seasonal storage with a dam located near Nordlingaalda, about 50 kilometers upstream from the mouths of the Tungnaa.

The Nordlingaalda damsite and reservoir area was recently mapped by the SEA on a scale of 1:20,000 with a five-meter contour interval. Downstream therefrom the only topographic maps available are those on scales of 1:50,000 with 20-meter contours, and 1:100,000 with 20-meter contours. The River profile, shown on Exhibit 4, has been surveyed by the SEA. Aerial photographs are available for the entire area, except for a ten-kilometer long band in the Thjorsa Gorge Section. No roads penetrate this undeveloped and uninhabited area.

DEVELOPMENT POSSIBILITIES

The Lower Section

The total fall in the reach of about 20 kilometers comprising the Lower Section is about 30 meters. There is a drop in the Thjorsa of about 15 meters as it passes, for 4.5 kilometers, the mouths of the distributaries of the Tungnaa. Beginning at the mouth of Blautakvisl Distributary where the water level is at about 288 meters, the braided section referred to above extends upstream for about eleven kilometers with a fall of only about nine meters. In the next five kilometers proceeding upstream, with a fall of six meters, the Thjorsa narrows and becomes steeper as it begins to emerge from the Thjorsa Gorge.

Part of the available head, above elevation 273 meters at the mouth of the Tungnaa, may possibly be developed by one of the alternative Projects, Burfell or Sultartangi discussed in Chapter XVII. On the basis of present information, feasible damsites do not exist throughout most of the downstream portion of this Section. A feasible damsite may exist towards the uppermost end of the Section, where it begins to leave the Thjorsa Gorge, but the low gradient and straight alignment could not justify the expense of water conductors.

More detailed mapping on a scale of 1:20,000 with five-meter contours, and geologic reconnaissance, should be accomplished ultimately in order to permit a more detailed evaluation.

The Thjorsa Gorge Section

The Thjorsa Gorge Section with its relatively concentrated great fall and favorable geologic setting appears to present excellent possibilities for power development, especially in combination with upstream storage. Much additional information is required in order to permit an appraisal of this potential. The comments which follow present our general observations and recommendations pointed towards achieving such an evaluation.

There is a natural fall of about 160 meters in a distance of about eight kilometers beginning about three kilometers upstream of Dynkur and extending downstream to an elevation of about 305 meters, a short distance downstream from Glufurleitarfoss. This reach includes a series of rapids and the two waterfalls referred to above. This reach may be developed for power by a dam at or near the upstream point, a tunnel to conduct the water to a tailrace at the downstream point, and a powerhouse. The powerhouse may be a surface station below Glufurleitarfoss or an underground station located at the most favorable point along the tunnel.

The fact that the Hreppar strata, forming the Gorge, intersect the River profile at a low angle means that it should be possible, by shifting the dam and powerhouse upstream or downstream, and by changing the altitude of the power tunnels, to take advantage of the best rock in the sequence and to avoid rock units that are apt to give trouble.

A single development of this general type would almost certainly be less costly than dividing the head between two or more developments. Such alternatives, however, should be studied during the planning phase.

More field information will be required to establish the headwater level. A low diversion dam and spillway in the reach between about one and three kilometers upstream from Dynkur, where the river was observed during our reconnaissance to split between two channels creating a generally favorable construction diversion situation, is definitely feasible. Such a diversion dam might have a headwater level from 475 meters up to elevation 490 meters, which is the River level at the waterfall, Hvanngiljafoss, located 4.5 kilometers upstream. It is not now known whether the level might be increased farther to provide additional head plus some seasonal storage. The small-scale maps indicate a potential reservoir surface area of about 30 square kilometers to elevation 540 meters. However, the area to the east of the proposed damsite was observed to be low and wide, such that a dam to this level would be large and costly. Regulation by a storage reservoir located farther upstream would almost certainly be more economical.

In view of the relatively straight alignment of the River, there now appears to be little choice as to which side of the River is the more favorable for the location of the power features.

Correlation studies made by the SEA[9] show an average annual flow of 132 kl/s for the Thjorsa River at Thjorsargljufur. We are not sure whether this correlation point is near Dynkur or near the Tungnaa mouth. The drainage area for the former of 2615 square kilometers compares with 2850 square kilometers for the latter. If the flow estimate is for a point towards the mouth of the Tungnaa, the average annual flow at Dynkur might be on the order of 125 kl/s. More detailed hydrological measurements and studies are required to establish discharge data at Dynkur. The storage required in an average year to equalize the flow, based on the average monthly discharges estimated by the correlation study, would amount to about 1000 million cubic meters. Drier years would require greater amounts of storage. The necessity for substantial upstream regulation is indicated clearly.

The relatively high head developed by a single plant favors a peaking installation and planning for the ultimate project should consider a capacity factor of 50 percent or less. This would require a rather large amount of pondage, or close flow correlation with an upstream storage project. Consideration may be given to an initial dam to about elevation 475 meters providing about 170 meters of gross head and which would be raised about 15 meters or more to provide pondage and added head at such time in the future as peaking capacity becomes justified.

The ultimate installed capacity based on a station flow capacity of 250 kl/s, corresponding to a 50 percent plant factor with a fully regulated average flow of 125 kl/s, would range from about 325, 000 kilowatts to 360, 000 kilowatts for headwater elevations of 475 meters and 490 meters, respectively. The gross average annual energy production with nearly full regulation of a flow of 125 kl/s would be about 1500 million kilowatt-hours and 1600 million kilowatthours for the two headwater levels, respectively.

The airphotos indicate that the Thjorsa Gorge is cut in a sequence of layered rocks in which resistant cliff-forming units are interbedded with weaker bench-forming units. The dip is gentle to the southeast. Because they are on strike with Hreppar rocks exposed in Burfell and Stangarfjall, and are closely similar in topographic expression, it seems likely that the rocks underlying the Gorge area are Hreppar. If this is true, the sequence consists chiefly of basalt flows and sedimentary units that are characteristically strong and low in permeability, that is, rocks that are generally excellent for most engineering purposes. It is probable, on the basis of observations to the south, that layers of pillow-palagonite breccia and other poorer quality rocks make up a small percentage of the sequence. Many tributary streams in the Gorge areas are aligned along a conspicuous set of master joints or faults trending about N70°E., and a less well-defined set trending about N.30° E.

The gologic mapping of the strip along the Gorge, where the rock sequence is best exposed, should be undertaken when the larger scale topography becomes available. Insofar as this is possible, the cartographic units should be individual flows and sedimentary members; on the basis of observations elsewhere, it is likely that some of the Hreppar strata may be continuous throughout the entire Gorge area. Knowledge of the structural relationships and the engineering properties of the flows and sedimentary units, gained in the course of mapping the River strip, will be adequate for preliminary layouts of engineering works in any part of the Gorge; drilling at possible sites, in a second stage of the investigation, will be chiefly to check inferences based on a comprehensive understanding of the geology, and to determine permeability.

Our geologic evaluations have been based largely on study of the aerial photographs; and our field reconnaissance to the uppermost reaches of the Gorge and to other areas.

The initial field investigations should consist of topographic and geologic mapping of the entire Thjorsa Gorge reach for about one kilometer on each side of the River. The topography should be on a scale of 1;20,000 with five-meter contours where feasible.

Staff gages should be established and rated in the subsequent Project Planning phase at the possible damsites and tailwater points. Check discharge measurements should be made near Dynkur to permit correlation with the Nordlingaalda gage.

The Upper Section

The Upper Section does not appear to contain any good power sites, but does present possibilities for storage development. It appears reasonable to assume that the reservoir from the dam proposed above and located at the head of the Thjorsa Gorge would extend ultimately at least 4 3/4 kilometers upstream to the foot of the waterfall, Hvanngiljafoss, where the River level is 490 meters. This waterfall has a drop of about 15 meters in one-half kilometer. Additional head, possibly on the order of ten or fifteen meters, could be created by a dam at this point to permit a power project which may be economically feasible at some future time. It would be a relatively low-head, base-load plant, and upstream regulation would be essential. A dam near the upper end of the Thjorsa Gorge much above elevation 490 meters would flood out this potential project. No other power projects in the Upper Section appear feasible.

The possibilities of a storage dam and reservoir which prompted the recent large-scale mapping by the SEA in the Nordingaalda area, about 20 kilometers upstream from the Thjorsa Gorge, are verified by these maps. The site about one kilometer downstream of the tributary Svarta at about the 555-meter River contour on that map is topographically the most favorable; a dam about 400 meters long across the River section with a reservoir at elevation 580 meters would impound a lake with a surface area of about 55 square kilometers. Two dikes, one on each side of the River at low saddles, would also be required.

The geological relationships at this site are somewhat unfavorable in that both the bedrock and a terrace deposit which would underlie the right side of the dam would probably require special sealing operations to keep leakage within safe limits.

Exposures in the front of the terrace, viewed from the left (east) side of the River, show what appear to be southward-dipping forset beds which suggest that the terrace consists, at least in part, of a delta built into a lake by the Thjorsa during glacial times. In some parts of the scarp, layers of incoherent alluvium are interbedded with layers consisting of subangular rock fragments in a dense matrix of sandy and silty clay. This material shows no bedding nor sorting and could be readily mistaken for glacial till were it not for the fact that the layers are clearly parts of the deltaic forset structure. The contrast between the types of material probably represents variations in the silt and clay content of the glacial Thjorsa during the period of delta building.

Close examination of the terrace was not made during our reconnaisance and it is not known whether the delta was built during the recession of the last glacier or whether it was formed earlier and overriden by ice during the last glacial stage. In the former case it would be capped by alluvium; in the latter the cover would be glacial till. Coarse openwork gravel is characteristic of deltas built into glacial lakes elsewhere, and on that basis the terrace may be so permeable that a cutoff wall or grout curtain will be needed.

The right terrace deposit rests with a small angular discordance on a sequence of interbedded lava flows and sediments, with the contact five to ten meters above the River along most of the front of the terrace. A fairly large artesian spring wells out from rock on the right bank just above the River level near the proposed axis. Sigurdjon Rist informed us that at low-water stages numerous similar springs may be seen issuing from joints in the bedrock floor of the River channel in that vicinity.

The nature of the aquifers for the springs is suggested by exposures in the riverward face of a hill just southwest of the site on the east side of the River. A sheet of basalt which crops out about ten meters above the River consists largely of breccia and pillows probably formed as a result of a lava flow into a lake. At and just above River level firmly cemented openwork gravel interlenses irregularly with dense till-like material. It is possible that these sediments lie against an older valley side and are part of the delta deposits described above. However, it is more likely that they are older and pass back into the bank under the overlying brecciated basalt as part of the bedrock sequence. In this latter case, either the openwork gravel or the brecciated basalt could be the source of the artesian springs. It is evident in any case, that the bedrock sequence includes layers that are very permeable, and that special foundation treatment will be required.

The project planning phase must include studies of alternative sites for a storage dam and reservoir in order to evaluate costs and benefits, regardless of the general overall quality of the Nordlingaalda site described above. The aerial photographs and large-scale maps show one possible site about 1.3 kilometers farther upstream near the confluence of the Svarta at River contour 557 meters, and a second about 1.0 kilometers even farther upstream at River contour 560 meters. Each of these sites is topographically suitable for a dam to a reservoir elevation of 580 meters. Each dam is considerably longer and somewhat lower than the equivalent dam at the Nordlingaalda Site, and the reservoir created would likewise be somewhat smaller. A narrows about two kilometers downstream from the Svarta Junction and just upstream from the 545-meter River contour is topographically favorable for a dam with a 570-meter elevation reservoir or somewhat higher. It would require dikes in saddles east and west of the River. Two kilometers farther downstream, at River contour 535, a damsite to reservoir elevation 560 meters or slightly higher is located where a rock island splits the Thjorsa channel. These several possible sites permit consideration of the possibility for two dams with smaller reservoirs than that of a possibly larger single dam and reservoir. The planning studies, which would take into consideration progressive development of the hydroelectric resources, should consider these various alternatives.

The almost certain need for full utilization of any storage developed in the Noordlingaalda area nullifies any consideration of at-site power development.

Some additional head downstream from the storage dam in the Upper Section may never be feasible of economic power development.

Correlation studies made by the SEA[9] show an estimated average annual discharge of the Thjorsa River at Nordlingaalda of 99 kl/s. On this basis the annual yield would be about 3100 million cubic meters. Storage equivalent to 75 percent of the annual yield would be about 2400 million cubic meters. This quantity may not be feasible of economic development on the Upper Thjorsa. Reservoir area and volume curves prepared by the SEA for the Nordlingaalda Site show a useful storage of 500 million and 1,200 million cubic meters at reservoir elevations 585 and 590 meters, respectively. The volume of alternative or supplemental seasonal storage possibly available with a high dam near Dynkur can be determined only after detailed mapping of that reservoir area. In any event, it appears evident that the maximum amount of storage feasible should be considered in the long-range development of the water resources of the Thjorsa River Basin.

The field investigations required in the Upper Section will include geologic mapping and additional topographic mapping. The 1:20,000 scale topography with contours at five-meter intervals or less should be extended to join the mapping recommended for the Thjorsa Gorge Section and would include the reservoir area for the uppermost dam in that reach.

The requirements for geologic mapping would be substantially the same as recommended above for the Thjorsa Gorge Section. The available maps in the Nordlingaalda area permit an early start in that vicinity. The mapping of the overburden in that area will be of special importance because of the factors discussed above. It is not known whether the bedrock of the

Upper Section is a part of the Hreppar Series or whether it is younger. In any case, working out the detailed stratigraphy will be more difficult and less certain throughout the open valley of the Upper Section than in the Gorge because of the cover of glacial material.

Drilling and permeability tests will be required prior to any evaluation of the alternatives for the site of a storage dam or dams in the Nordlingaalda Area. This drilling may need to be rather extensive because of the several permeable zones revealed by our reconnaissance and discussed above. Churn drilling will probably represent the best method. Initial drilling should be concentrated at the topographically more favorable Nordlingaalda Site. It is probable that at that Site not less than twelve drill holes will be required to permit even a preliminary appraisal. Several times that number appear necessary for the final project planning and detailed design phases of the selected site or sites.

Other field investigations will include establishing and rating a stage gage at each selected site, and reconnaissance for an access route and for construction materials.

CONSTRUCTION MATERIALS

The only source of concrete aggregates or rockfill and filter materials noted during our reconnaissance were the basalts. They should be abundant in the Gorge Section, but exposures are infrequent in the Upper Section except at moderately high elevation. The morainal material, copious in the Nordlingaalda Area, may be suitable for processing as core material or for earthfill construction. Detailed reconnaissance will be required to locate suitable deposits for all required construction material.

CHAPTER XIII

T UNGNAARKROKUR PROJECT

GENERAL TOPOGRAPHY AND GEOLOGY

The Tungnaarkrokur Project is located on the Tungnaa about 27 kilometers upstream of its junction with the Thjorsa. It can develop about 75 meters of fall between elevation 425 and 500 meters where the River makes two bends, occupied by falls and rapids, within a gorge in its generally westerly alignment. Some aspects of the geology of the Project are discussed in the Thoroddsen Report[1]. These were supplemented by our reconnaissance.

The essential geologic elements of the Tungnaarkrokur area are a spur of rolling topographic form (Sigalda) developed on the Palagonite Formation, surrounded on the southeast and south by the Thjorsa lava plain. The spur is about two kilometers wide where it is crossed by the Tungnaa. The Thjorsa lava flowed northwestward, spreading through saddles between Palagonite hills which trend southwestward in rough alignment with the trend of the spur; the hills stand as low islands above the lava plain.

As noted in the Thoroddsen Report, three separate Thjorsa flows, numbered I to III in order of decreasing age, advanced into the embayment east of the spur. Flow III did not quite reach the River in this area. The distal part of Flow I is deeply covered by lacustrine and fluviatile sediments, and there is a thin sedimentary cover on Flow II beyond the overlapping end of Flow III. This cover extends to an altitude of about 500 meters; a shoreline at about the same altitude is conspicuous on the north side of the embayment. It is evident that the River is now incised across the spur in the position of a saddle which served as the spillway of the lava-dammed lake represented by the sediments and the shoreline, but it is not clear whether the formation of the lake and the diversion of the Tungnaa to its present position was accomplished primarily by Flow I or primarily by Flow II. It is possible, for example, that a lake impounded by Flow I was drained by down-cutting at the outlet or was completely filled with sediments prior to the formation of a second lake by Flow II. Or it may be that Flow II merely raised to a higher level (to about 500 meters) the water surface of a lake formed by Flow I. Perhaps this question will be answered by a study of the lacustrine and fluviatile sediments carried on during September, 1959, under the direction of Kjartansson. The stratigraphic complexities that may be found in the sediments, and the relationship of the sediments to the lava flows will bear importantly on the problem of reservoir tightness.

The falls and rapids in the gorge which extends upstream from the point where the Tungnaa enters the spur evidently represent the steepening of profile caused by diversion of the River to a new course by the Thjorsa lava. About half way through the spur the River turns northward along the eastern margin of a large splay of gravel; the Skeggjafoss waterfall at the north end of the gravel deposit is located on a ridge of resistant basalt which was encountered by the River as it cut down in a position assumed when the gravel was deposited. It is likely that the deposition of the gravel occurred at the time of breaching of the Palagonite dam just upstream, but this is not certain. For present purposes the significant point is that, whatever the time of deposition, the gravel occupies a depression in original Palagonite topography. The fact that sheets of indurated till and/or talus which lie against the lower slopes of the surrounding hills commonly pass downward below the River proves that the rock surface under the gravel is in some places well below the River level.

Topographic maps are available on a scale of 1:20,000 with five-meter contours for the entire Project area, including the proposed reservoir. Topography on a scale of 1:5,000 with a two-meter contour interval covers a width of about 500 meters on each side of the River through the gorge. The River profile has also been surveyed.

Eight drill holes have been completed in the lava plain to the south and southwest of the Project area to develop the stratigraphy and to determine groundwater tables. Four of these holes were drilled in the four lava-filled channels between the Palagonite hills of the southwestward trend from the Project area. Three of these penetrated through the lava to the bedrock encountered at elevations 474, 421, and 426 meters, respectively, proceeding southwest. The fourth hole, farther to the southwest did not reach bedrock. Groundwater was not reached in the first hole, and was encountered at elevation 447, 455, and 460, respectively, in the other holes, proceeding southwestward.

The other four holes were drilled in the lava at approximately regular intervals for 2.5 kilometers southward from the gorge to determine the elevation of the groundwater table, which was nearly level at about elevation 475 meters. A ninth hole was drilled in the Palagonite within the south wall gorge, approximately in the center thereof, at the damsite proposed by Thoroddsen.

The area of the Project is in an undeveloped and uninhabited area. An adequate access road for construction and future operation will be required.

DEVELOPMENT ALTERNATIVES

Reservoir

A dam located within the gorge will be required to develop a portion of the available head up to about 480 meters elevation. This dam may be constructed to a maximum normal water surface elevation of 500 meters, and thus provide seasonal storage (and additional head) in the amount of about 200 million cubic meters. The outline of a reservoir to this elevation is shown on Exhibit 10.

Elevation 500 is the level of the original lava-dammed lake and is considered the maximum level feasible of development. The Thjorsa lavas form the bedrock under the proposed reservoir on the bottom and southwest sides, and the Palagonite retains the side north and east of the River. The lava dips towards the River. All of the lowest lava (Flow I) and the northern edge of the overlying Flow II are to a very large extent covered with alluvial gravel, and silt and clay deposits of the ancient lake. The edge of the third lava sheet (Flow III) is farther south and the alluvial deposits do not cover that edge, but it is not apparent whether or not they extend under it. The two oldest lava sheets are exposed, together with their highly pervious contacts, on the left side wall within the gorge upstream from any proposed damsite.

There are two questions regarding reservoir tightness that apply to all schemes which would impound water in the proposed reservoir: (1) Will there be excessive loss of water through the lava via the gaps between the Palagonite hills southwest of the site ?; and (2) will the Palagonite itself require treatment in the abutments of the dam and elsewhere in the spur ? That there may be serious leakage through the lava-filled gaps is indicated by the low level of the watertable in the lava, and by the hydraulic gradient. The four holes along a line straight south from the gorge showed the watertable at about elevation 475, while in bore holes located in the gaps, four to five kilometers to the west, the watertable was about 20 meters lower. At worst, it might be impossible to raise the level in the reservoir above 480 or 490 meters, even with no water passing through the powerhouse.

It is possible, on the other hand, that the reservoir may stand at elevations 495 to 500 meters with no significant loss of water through the lava. This view depends largely on the fact that, as indicated by the shoreline and the sediments, the lake impounded by Flow II stood at an altitude of about 500 meters for many hundreds of years. It is safe to assume that the watertable divide to the south was then about the same altitude (475 meters) as at the present time, and that the lake existed because the surfaces of Flows I and II were at least partially sealed by sediments. This does not mean, however, that the same former lake basin is suitable for a reservoir because (1) the seepage loss from the lake might have been at a rate that would be intolerable in a hydroelectric reservoir, and (2) because the cutting of the gorge has exposed flow contacts that did not crop out on the floor of the lake. Large springs issue from these contacts within the gorge. If they are freely connected through open-work contact zones with the groundwater table to the south at elevation 475 meters, the leakage may be very serious, as indicated above. If the water issuing from the springs is derived from the Tungnaa channel upstream and from precipitation on the nearby parts of the lava plain, and if the spring openings are not freely connected with the watertable to the south, the leakage may be negligible.

The groundwater data now in hand does not answer these questions. The most elaborate exploratory program within reason will not provide a close evaluation of the leakage for various reservoir water levels, nor will it indicate what sealing measures should be undertaken to assure a given degree of tightness of the reservoir. The best basis for determining whether sealing measures are needed, and, if so, the most efficient design of such measures, is to test the reservoir basin by flooding.

If this "wait-and-see" policy is adopted, the powerplant and intake works must be designed to operate temporarily at levels as low as 480 meters. The actual rate of water loss at reservoir levels between elevations 480 and 500 meters will indicate whether sealing measures are justified, that is, whether steps should be taken to accelerate the expected natural slow silting up of voids. If there is need for such measures, the new configuration of the groundwater table will indicate whether it is preferable (1) to seal the reservoir sides by blanketing at the specific places where needed, or (2) to cut off the flow through the lavafilled gaps by grouting the flow contacts.

The treatment of the foundations in the immediate vicinity of the dam to reduce reservoir leakage is discussed hereinafter. With respect to the Palagonite which would retain a substantial portion of the reservoir to the west and north, the extreme and unpredictable variation in the strength and permeability of that Formation means that there is a possibility of trouble wherever the engineering work causes a marked steepening of the hydraulic gradient in this material; that is, anywhere along the length of the spur.

The spur should be mapped in as much detail as is practicable early in the exploration program, with special attention to zones of weakness of various types, especially where these are associated with seeps. It should be noted in this connection that nearly all of the surface, except steep slopes undercut by the River, is concealed by a mantle of indurated till, talus, or solifluction deposits; even the most careful mapping will be ineffective in the covered areas. Exploration by drilling is, of course, out of the question; the best policy is to take certain precautionary measures and then to "wait and see" what happens when the reservoir is tested by flooding. These measures include placing weirs on all seeps and drilling observation wells in critical places.

The worst possible relationship is a combination of a large body of weak material with a high void ratio lying behind a wall of impermeable material in the west slope of the spur, so that water seeping from the reservoir builds up in a subsurface pool to cause a sudden sluffing away of the wall accompanied by a possibly disastrous outburst of water and debris. Observation wells are needed wherever geologic study suggests that such a condition may exist.

The most sensitive-looking place on the spur is just southwest of the lower damsite in the Palagonite where the topographic form suggests post-glacial sliding on a large scale. The area needs special study to determine (a) the cause of the localization of erosion and (b) whether the condition constitutes a danger to the dam.

The planning and design studies will develop the economic height of the reservoir, initially and ultimately. An initial reservoir to about elevation 480, with the dam designed for future raising to create a maximum reservoir elevation of 500 may be indicated. It is our present opinion, however, that the design should be based on an initial dam adequate to create a reservoir to this maximum feasible level. The level, as a minimum, could probably be attained during flood periods, thus permitting gradual silting of the reservoir floor and consequent reduction of leakage, should this show up as a problem. The seasonal storage, when attained, would be valuable for reregulation of upstream storage, such as from Thorisvatn, and for regulation at-site and at downstream points.

Dam and Spillway

The dam to create the reservoir and develop a portion of the total available head would be located in the gorge at or upstream from the point where the Tungnaa cuts through the Palagonite of the Sigalda. Plans involving dams at two different locations were presented by Thoroddsen[1]. These are designated as Site A and Site B on Exhibit 11. We concur that Site A does not warrant further consideration at this time. We propose consideration of Site C as a feasible alternative to Site B. The right (north) abutment at either Site would be in Palagonite, and rises rather steeply from the present River's edge. This is also true of the left (south) abutment at Site C. The riverbed at both Sites is in Palagonite. The lower one-half of the left abutment at Site B is a Palagonite hump overlain by Flow II of the Thjorsa lava. However, Flow I is exposed in the gorge walls at lower elevations, both upstream and downstream from the hump. The surface of Flow II is below the planned reservoir elevation of 500 meters for a distance of about 200 meters to the south and to about the distal edge of Flow III. A relatively low dike would be required through this reach.

The large springs previously referred to issue from the gorge walls at the boundary between the Palagonite and the lava both upstream and downstream from Site B. The contact between Flows I and II is also permeable.

One of the principal difficulties associated with Site B is the need for an extensive grouting operation to seal these highly permeable contacts. These permeable zones contain irregularly shaped bodies of openwork talus breccia that underlie a mantle of indurated till or talus which passes beneath the Thjorsa flows in many places in the vicinity of the Site. The very high permeability indicated by the copious discharge of springs on the gorge wall and the large size of interconnected openings seen in outcrops of the flow contacts, mean that a mere lengthening of the seepage path by a grout curtain in the immediate vicinity of the left abutment will not be effective; a positive cutoff extending from the dam downstream to tie to the Palagonite spur is required. The length of the curtain is about 700 meters. The depth to the contact between Flows I and II is about seven meters and the thickness of the zone that will accept grout averages about two meters. The additional depth to the contact at the base of the lava varies greatly depending on the form of the buried topography; it may average about ten meters. The thickness of the zone to be grouted also varies greatly because of the irregularly shaped bodies of superficial material mentioned above--it may average three meters.

Estimates of cost of the curtain must take into account special procedures that may be required to seal parts of the contacts through which groundwater is now moving to the springs at high velocities.

Rockfill construction is recommended for either Site B or C. Our observations of the Palagonite raise serious questions as to the adequacy of the strength and other foundation properties of that rock for either concrete gravity or concrete arch construction. Further investigations may possibly not confirm this tentative conclusion for either or both types. Almost certainly, though, rockfill construction would be less costly than concrete gravity construction. Either a central impervious core or sloping upstream impervious core would be suitable. The latter may be preferable from a general construction standpoint. Material from spillway and tunnel excavation may, in part, be suitable for selected zones within the rockfill.

A concrete-lined diversion tunnel would be required at either Site B or C. It may, if found desirable, be adapted for a low-level release at relatively low cost. Alternatively, it would be permanently plugged after diversion with concrete.

Grouting of foundations for the dam and spillway, and to some distance to the right in the Palagonite, will be required. With Site B, the curtain grouting may need to extend southward only to its intersection with the other line of curtain grouting referred to above.

A gated chute type of spillway is recommended for either Site B or C. The spillway should preferably be located on the right bank in order to provide some ice and silt control in front of the power intake structure. Since much the shorter route for the power development is in a northwesterly direction through the Palagonite spur, the natural location for the intake is on the right bank. The intake should be set as deep as is feasible in order to operate in the most satisfactory manner with a pool elevation of 480 meters, as discussed above. By keeping the reservoir at elevation 490 meters or higher during ice runs, the risk of the intake being blocked will be greatly reduced. Ice-passing gates and a sluice gate for desilting should be provided in front of the intake and preferably discharge normal to it for most efficient operation. Tainter gates would be the most economical type. The bay nearest the intake should be fitted with a gate which can recess slightly to pass ice over the top with minimum loss of water and greatest effectiveness. This gate could also be of the tainter type.

The rockfill dam at Site B will require only about one-half the volume of similar construction at Site C. The latter will require a total volume on the order of one million cubic meters. The diversion tunnel should be slightly shorter at Site B. The cost differential for the direct power features as between the two Sites appears relatively small. On the other hand, the long grout curtain required to cut off short-path reservoir leakage through the lavas, not required at Site C, is almost certain to be very expensive, perhaps costing on the order of one million dollars (US).

Investigations and studies of both Sites will be required to establish an adequate basis for comparison and ultimate selection. At the present time we tend to favor Site C, principally because of the many uncertainties associated with the grout curtain problem, and which cannot be fully evaluated short of actual construction.

Power Features

The head can be economically developed for power to a point downstream slightly below Skeggjafoss where the River surface is approximately 425 meters. Downstream therefrom the gradient is only about 0.2 percent and can be developed best by the proposed Hrauneyjafoss Project. The head from the reservoir surface to this selected tailwater can best be developed largely, if not entirely, by tunnels. The powerstation may be either underground or at the surface.

The principal problem associated with the power features is the quality of the Palagonite rocks associated with the underground excavations. The rock has to this date not been adequately investigated to allow definite planning of these features. The principal considerations are permeability and strength. In places it may possibly be too weak and permeable to allow underground excavation and lining below the groundwater table within tolerable cost limits. Conversely, at other places it may be adequately strong and watertight. An extensive drilling program is required to answer these important uncertainties.

A headrace tunnel can be expected to be well above the groundwater table and contain no water problems. Even the most favorable route selected after detailed investigations may require some support during driving. Concrete lining would be required. A surge chamber will be needed if the length of the headrace tunnel and penstocks exceeds the allowable for turbine regulation. The surge tank would likely be excavated largely or entirely in rock, and placing this feature in a favorable site located by drilling would have an important bearing on the headrace tunnel alignment.

The selection of an underground powerstation as opposed to a surface powerhouse should not be made until subsurface investigations have definitely located suitable rock conditions for underground construction of this relatively great magnitude. Inasmuch as such a location would be within the groundwater zone, water problems, possibly serious, can be expected. Support during excavation may be required, and full concrete lining of the roof is almost a certainty. Similar problems may be expected with respect to the tailrace surge chamber and to the penstocks, particularly where their excavation would be below the groundwater table. It will probably be essential that all excavation and concrete (other than the machinery installation or lining behind steel penstocks) associated with future generating units would need to be accomplished with the initial construction.

All tailtunnel excavation will present some water problems, since it would be below the groundwater table throughout. Some support and full concrete lining would almost certainly be required. The route would be selected only after thorough investigations. An alignment which would pass under the riverbed is to be avoided unless the feasibility as regards adequate rock cover and watertightness has been established beyond question by thorough subsurface investigations. Any failure at such a point would be disastrous.

The planning studies should include an alternative with a surface powerhouse located on the right bank of the River below Skeggjafoss and served by surface (or underground) penstocks connecting through a surge tank cut with a headrace tunnel. The minimum of water problems would occur with such a plan. The Palagonite is suitable as a foundation rock for the powerhouse, surge tank, and penstock anchors and supports. Future unit provisions might be more minimal than with an underground powerstation.

Control valves will be required in all penstocks connecting with a surge tank or headrace tunnel. If the penstocks extend to the intake, as may be the case with an underground powerstation near the dam, individual gates at the intake should suffice for such control.

One possible layout of the power features is shown, principally for illustrative purposes, on Plate 11. In this case, the dam is situated at Site B, but the general arrangement would be equally applicable with the dam at Site C. An underground powerstation is served by individual penstocks extending to the intake. The powerhouse discharge with Route I is conducted by tail-tunnel and canal along the shortest route to return to the River below Skeggjafoss. From the River to the northwest, this alignment crosses the large gravel splay and would be in canal where the tunnel cover is inadequate. Cut and cover conduit could be used if any portion under the River was unsuitable for tunnel, but would require expensive temporary diversion of the River during such a construction operation. Alternatively, the canal could extend across the present riverbed. This would require a large channel, as shown on Exhibit 11, through the gravel splay for diversion of the water passed over the spillway. A retaining wall would be required to protect the tailrace channel. This alternative might only be feasible if the river diversion excavation could be used economically in the dam construction.

The location of the underground powerstation is flexible within some limits with this illustrative plan. A greater distance from the intake may require a surge tank, headrace tunnel, and differently arranged penstocks.

This illustrative plan provides minimal quantities assuming satisfactory tunneling conditions exist below and beyond the River, since it follows the shortest route between headwater and tailwater. The distance would be approximately equal from an intake at Damsite C. The length of the water conductors would be greater if located entirely on the east side of the River, such as along Route II on Exhibit 11. About all that can be said at this time for the scheme as illustrated is that it represents one of possibly a number of alternatives which may be studied in evolving the final adopted design.

WATER SUPPLY, POWER AND ENERGY

Two automatic, continuous recording stage gages have been established on the Tungnaa River. One, established in November 1958, is located at Vatnaoldur, upstream from Tungnaarkrokur, where the drainage area of 1350 square kilometers is about thirteen percent less. The other gage, established in October 1959, is located at Hald, a short distance upstream from the junction of the Tungnaa with the Thjorsa. Discharges for the first four months since installation of the Vatnaoldur gage are included in the Thoroddsen Report[(1)]. Neither of these records presently cover an adequate period of time to use as a basis for power and energy estimates.

Estimates made by the SEA[(9)] based on correlation with the Thjorsa River records at Urridafoss gave an average annual discharge at Tungnaarkrokur of 98 kl/s. Flows during the three low months in the winter were estimated to be about 67 kl/s. Summer flows were nearly double that amount or greater. Diversion of the Kaldakvisl and Thorisos into the Thorisvatn Storage Reservoir for release to the Tungnaa upstream from Tungnaarkrokur could add about 47 kl/s to the estimated average annual discharge, for a total of 145 kl/s. Monthly average discharges for these two Rivers, estimated on the same correlation basis with the Thjorsa at Urridafoss, indicate that the combined flow at Tungnaarkrokur can be completely evened out to the average of 145 kl/s with about 500 million cubic meters of storage. Available seasonal storage volume in the Tungnaarkrokur and Thorisvatn Storage reservoirs would be about three and one-half times that amount. However, it must be recognized that all storage would be utilized for maximum system benefit rather than for the benefit of a single project. This would be true for the storage discussed above as well as for any storage ultimately provided on the Upper Tungnaa, including possible diversion from Lake Langisjor, all if found feasible and economic. Accordingly, maximum regulated discharges at Tungnaarkrokur integrated in the overall ultimate Southwest Iceland Power Supply System may be substantially in excess of the aforementioned average of 145 kl/s. With allowance for peaking capacity and head reduction when the Tungnaarkrokur reservoir is drawn down but without allowance for Langisjor diversion, the ultimate installed flow capacity at Tungnaarkrokur may be somewhat in excess of 200 kl/s. The ultimate installed power capacity, then, might range from about 110,000 to 130,000 kilowatts. The initial and ultimate installed capacity at Tungnaarkrokur can only be established after accomplishing a comprehensive System Operation Study.

The average gross annual energy production at Tungnaarkrokur, based on the estimated fully regulated average annual discharge of 145 kl/s would, with some allowance for head reduction by the at-site reservoir operation, amount to about 700 million kilowatthours. Years drier than average would reduce production, but this may be offset by the use of hold-over storage in cyclic storage reservoirs, such as Thorisvatn.

FIELD INVESTIGATIONS

Topography

The existing topographic maps of the Project are adequate for planning purposes, but would require supplementing in more detail for design purposes. Maps on a scale of 1:1000, with one-meter contours should be prepared for the site of all structures selected for design, and for all selected construction material borrow areas. The detailed field investigations may show the need for other supplemental mapping in greater detail than now available, such as at reservoir rim areas which may be critical from a geologic standpoint, and for the access road, camp areas, etc.

Subsurface Investigations

The complexities of the geologic conditions will require extensive subsurface investigations prior to detailed planning or design. These are required principally for further evaluation of potential reservoir leakage and appraisal of the power features, as discussed above. It is our opinion that churn drilling will be more effective than diamond core drilling for borings and permeability tests, though the latter may be better in some instances.

With respect to long-path leakage from the reservoir through lava-filled gaps in the Palagonite ridge, we recommend at least five additional borings to below the present watertable in the lava plain to the south and west. Some of these should extend to the Palagonite surface if at reasonable depth. Standard permeability tests accomplished during drilling are recommended, but core is not important. These, as well as holes previously drilled, should be preserved for regular observation of the form of the groundwater table both prior to the completion of construction, during reservoir filling, and thereafter into the operation period. Studies of spring and groundwater temperatures and chemical characteristics should be continued. An attempt should be made to determine the rate and direction of water flow under the lava plain by the use of tracers. Additional groundwater observation wells may be required at geologically critical areas in the Palagonite of the reservoir rim, as discussed above, but most or all of these may be accomplished during the construction stage.

At least three borings will be required along the general route of the short-path leakage from Damsite B for planning purposes. These should be extended well into the underlying Palagonite and tested for permeability during drilling, especially at each contact. These tests will provide data for estimating grout take and are basic to the overall evaluation of a dam at that Site. If Site B is selected for design, additional borings will be required to establish the alignment of the most economical cutoff route. Grouting tests may also be desirable.

Borings will be required for planning purposes principally to determine the permeability of the Palagonite in the abutments of each of the two possible damsites. Four borings at each Site may be adequate--one near the top of each abutment and two at low level. Additional borings and associated permeability tests will be required for design purposes at the selected Site. Holes in the abutment should be carried to below River grade, and those at low level should extend at least fifteen meters below the bedrock floor of the channel. All of these holes, other than ones which may be located in the River, should be preserved for groundwater table observations, with particular study as regards the relation of that table to nearby River stages. Diamond core drill borings and tests to determine the strength of the Palagonite will be required in the design phase at the site of all surface concrete structures such as the intake, spillway, and surface powerhouse (if selected), and along the route of the diversion tunnel.

Subsurface investigations to establish the location in plan and elevation of the power features are of critical importance for reasons noted above. The detailed geologic mapping, previously discussed, should extend throughout the area of the Project works, and should precede most or all of the underground explorations. Among other things, this survey would develop data regarding the structure, trend of faults and joint zones, void ratios, and other physical properties of the Palagonite.

Drilling based on the geologic studies should initially be directed towards discovering the most favorable (if any) location for an underground powerstation. Accordingly, the boring and permeability tests accomplished as each hole is drilled should extend down to about elevation 410 meters, and be subjected to permeability tests at regular intervals to determine whether the water flows that may be anticipated are within limits that can be handled by pumping and also to determine whether the strength of the Palagonite is such that it will stand in the powerstation walls and roof, and that it will not pipe by water flowing under high pressure. If a suitable site is discovered, the location of the other underground excavations, such as surge tanks, access shafts and tunnels, and the water conductors (particularly the tail-tunnel) should be verified by drilling to the required grade. It is not possible at this time to estimate the number of bore holes required for the planning phase; but twenty would appear to be a minimum. Additional drilling will, of course, be required during the design phase for all structures of the adopted plan, whether involving an underground powerstation or a surface powerhouse.

We recommend an exploratory tunnel (or shaft and drift) into the region of the powerstation in the event that an underground structure is selected for design. Such an exploration would give considerably more detailed information with regard to leakage and rock characteristics than can be accomplished by borings, and might verify the feasibility of the location prior to actual construction. Consideration should be given to locating this feature to serve some ultimate purpose, such as for a pilot tunnel, access, electrical, or ventilation facilities.

In general, all bore holes should be preserved for the continuing measurement of the groundwater table. Staff gages should be installed and rated at each of the two proposed damsites and at tailwater below Skeggjafoss.

CONSTRUCTION MATERIALS

Investigations will be required for concrete aggregates. The big gravel splay located in the bend of the River to the south of Skeggjafoss appears suitable for processing into coarse aggregate, and also may contain some fines. Test pits should be dug throughout the area, and samples obtained and tested for suitability. The Thjorsa lavas are doubtless suitable for processing for aggregate and should be tested. The Palagonite from required excavations is not considered suitable. Deposits of fine aggregates are believed to occur in the old lake bed formed by the lava dams at both Tungnaarkrokur and Hrauneyjafoss. Reconnaissance should be made of these areas, and samples obtained, and tested, from test pits in areas of suitable material located thereby.

These old lake beds almost certainly contain material suitable for the core of a rockfill dam. The reconnaissance already under way in the ancient lake bed upstream from Tungnaarkrokur should be continued, aimed toward developing suitable deposits. Laboratory tests of samples are, of course, necessary. The clay layers observed by us near River level in the old lake bed are too "fat" to be workable. Layers of clay, silt, and sand of suitable composition almost certainly occur at higher levels.

A considerable volume of shell material would be required for the proposed rockfill dam. The large gravel splay referred to above must certainly contain a large volume of suitable material which may also be processed for filter material. The investigations in this area should be extensive enough to cover required explorations for both purposes. The Thjorsa lavas are also probably suitable for processing into both shell and filter material. Tests at the time of design should include a quarry test blast to study breakage patterns, as well as crushing tests to check the quality for both concrete aggregates and filter material. Material from required excavations in the Palagonite may be, in part, suitable for select zones in the shell; though this is somewhat doubtful.

Investigations will also be required along the selected route of the access road to develop deposits of embankment, ballast, and road metal for that construction.

CHAPTER XIV

HRAUNEYJAFOSS PROJECT

GENERAL TOPOGRAPHY AND GEOLOGY

The Hrauneyjafoss Project would be located on the Tungnaa River about fifteen kilometers above its junction with the Thjorsa River. It is located downstream from the Tungnaarkrokur Project and its reservoir would extend to the tailwater of that plant at elevation 425 meters. The total gross head which it would develop might vary between 70 meters and 100 meters, depending on which of several alternatives would be selected for the power features of the Project.

The geologic and topographic background relationships are in all essential respects the same as at Tungnaarkrokur. The River is incised at the north margin of a Thjorsa lava flow which spread westward through gaps in the Palagonite ridge that extends southwesterly from Tungnaarkrokur. A somewhat similar Palagonite ridge, generally parallel in direction and with lava-filled gaps, extends through the Project area. There are three contrasted segments of the River proceeding upstream through the Project area: (1) the gorge at the margin of the lave; (2) a segment next upstream in which the River is still on the surface of the youngest Thjorsa flow in shallow channels split around lava islands; and (3) a segment extending to the Tungnaarkrokur tailwater in which the River braids on an alluvial plain formed by filling of an ancient lake impounded by the lava.

Nearly all of the Project area is covered by recent SEA topographic maps on a scale of 1:5000 with two-meter contours. The principal exception is an area to the north. Maps on a scale of 1:20,000 and with five-meter contours are available for the entire area.

No detailed geologic mapping or drilling has been accomplished. Some geologic aspects are discussed in the Thoroddsen Report [(1)], and have been supplemented by our reconnaissance.

The general area of the Project is undeveloped and uninhabited. It is accessible over a track in the favorable season, but a permanent access road will be required for construction and operation. This would be a spur from the Tungnaarkrokur access road (or vice versa). The Tungnaa is not bridged; therefore, a temporary construction bridge would be required until the dam with a roadway is completed.

DEVELOPMENT ALTERNATIVES

Reservoir

The reservoir would be limited to a maximum normal elevation of 425 meters by the Tungnaarkrokur tailwater below Skeggjafoss. Excess leakage from the reservoir through the Thjorsa lava may limit this level to possibly as low as 420 meters unless provisions are made for reducing such possible leakage by grouting or by natural sealing.

As at the Tungnaarkrokur Project, all proposed damsites present two leakage problems, one along a short path which returns to the Tungnaa channel just downstream from the dam, and another along a long path through a lava plain to the south, the long seepage path is in this case through the Thjorsa lava around the south side of the mountain, Hrauneyja-fell. The distribution of barriers of Palagonite which stand above the lava plain and the generalized topography shown on the 1:100, 000-scale maps indicate that the hydraulic gradient is low. It is therefore possible that the seepage loss may be small even with the reservoir at its maximum level of 425 meters. But this level very nearly tops the divide just east of Hrauneyjafell, and the lava surface provides a large intake area; if flow contacts in the vicinity of the divide have large interconnected voids, the loss of water may be so great that treatment is required.

If this possible seepage path is not sealed, and/or if something less than a complete cutoff is constructed under the dam, it will be necessary to design the power intake works for temporary operation with the reservoir as low as elevation 420 meters. Maintaining the highest possible level during periods of peak River discharge will serve the double purpose of (1) blanketing the surface of the lava with sediment carried in suspension, and (2) reducing the movement of bedload from the braided channels at the head of the reservoir into the deeper part near the power intake.

The reservoir would not contain any seasonal storage, but ample pondage would be available for daily regulation. Reduction of volume by silting should not be significant after the construction of the Tungnaarkrokur Project. The silting referred to above to reduce leakage is desirable and would tend to favor the construction of Hrauneyjafoss in advance of Tungnaarkrokur.

We recommend full development to elevation 425 meters as an initial provision. If it develops that this level cannot be attained initially because of excessive leakage, we are confident that it can be within a reasonable time.

Dam and Spillway

Our alternative locations for the dam are shown on Exhibit 12. The two designated A and B, farthest upstream, were proposed by Thoroddsen [(1)]. We propose Sites C and D for consideration also during the planning phase, which would select one of the four sites for design and construction. No site farther downstream is feasible. The development of each Site has the similarity of a concrete gated spillway in the River section and a long, low, rockfill dike extending southward over the lava plain to the Palagonite hill, Hrauneyjafell. The overall length of the dike decreases proceeding downstream from Site A to Site D. Conversely, the average height increases. The dike would include an impervious core protected by filters, and sealed against piping at the foundation contact.

The permeability of the lavas will require a grout cutoff to prevent leakage from the reservoir. Field investigations will be required to establish the depth and length of the grout curtain. In all probability it will need to extend for the entire length under the spillway and the dike. The depth will be dependent principally on the location and permeability of the contacts. It is not now known whether there are one or two flows overlying the Palagonite bedrock.

The absence of this field information at this time prevents an adequate appraisal between the four alternative sites. Our preliminary estimates show that the fill volume increases proceeding downstream from Site A to Site D, but this may be offset by the corresponding reduced length of grout curtains in such a way that there may be no appreciable cost differential, and other factors will decide the final location. Each Site is favored by split channels, which will facilitate diversion. With Site D, diversion could be via the Hrauneyjakvisl channel, bypassing the River throughout the area of the Project works. This feature might have important construction and cost advantages.

The spillway at each Site would consist essentially of a concrete sill surmounted by piers and gates. The gates may be either of the tainter or fish-belly flap type. If the former is selected, the one nearest the intake should be designed to recess slightly to pass ice over the top without excess loss of water. The power intake should be contiguous with the spillway on the right (north) side and normal thereto. A silt sluice and an ice sluice should be incorporated in the right end of the spillway.

The spillway for Site D would be as close as reasonably feasible upstream from the Hrauneyjafoss waterfall. This may provide better hydraulic conditions downstream from the spillway than at the other Sites. The greater depth at Site D will probably permit of a more economical spillway structure and gates than at either of the other Sites. Also, the deeper intake will be a great advantage with regard to potential ice problems. The reservoir volume available for silt storage would increase proceeding from Site A to Site D.

At the present time, we tend to favor Site D as the location for the dam and spillway, principally because of the several advantages referred to above.

Power Features

The development of the head for power at the Hrauneyjafoss Project should be based on a joint consideration with the next proposed project downstream which we have herein designated the Lower Tungnaa Project. This latter site is located about six kilometers downstream from the mouth of the Kaldakvisl, where the Tungnaa is at about elevation 300 meters. The reservoir which it would create could cover the range of alternative tailwater elevations, from 325 meters to 355 meters, which are to be investigated for the Hrauneyjafoss Project. The principal point to be made is that the two Projects, to develop the head from 300 meters to 425 meters, must be considered in coordination to provide the most economic development of that total resource, and with due consideration of the time factor; the Lower Tungnaa Project may not become feasible economically as an addition to the System until many years after Hrauneyjafoss is placed in operation, thus possibly justifying greater initial head development at Hrauneyjafoss.

The Tungnaa River enters the gorge at the waterfall, Hrauneyjafoss, which has a drop of about 30 meters and is located a short distance downstream from Damsite D. A series of rapids and small waterfalls comprise the relatively steep gradient down to elevation 325 meters, proceeding for the next four kilometers downstream to a point about 1.5 kilometers upstream from the mouth of the Kaldakvisl. Several bends in the reach of the River under consideration for development shorten the alignment of the required water conductors. The available head is feasible of development by tunnels, with canals being used only for a portion or all of the tailrace with certain of the development alternatives.

We have indicated on Exhibit 12 four alternative approximate alignments for the water conductors to develop the available head. While shown on the drawing only for a dam at Site B, the development principles should be the same for any of the other three alternative damsites. However, the length of the water conductors would vary and it is, therefore, obvious that final selection of the damsite can be made only after joint consideration with the power features.

The four alternative water conductor alignments are designated as Routes I to IV on Exhibit 12. Routes I and II each extend to a tailwater elevation of about 325 meters and are thus alternatives within themselves dependent principally on relative geologic conditions. Each would require an underground powerstation with the tailrace tunnel much longer than the headrace tunnel. Development to this tailwater level would provide a gross head of about 100 meters, with a corresponding head at the Lower Tungnaa Project of about 25 meters. The length of the water conductors would be about three kilometers. Route II would be entirely on the right (northwest) side of the River and is basically the same as proposed by Thoroddsen [(1)]. The tail-tunnel of Route I would cross under the River from the right to the left side.

Route III is based on the fact that a small tributary, which roughly parallels the Tungnaa to the north, is at a lower level than the main River at an equal distance from the Hrauneyjafoss reservoir. The tailwater level would be about 340 meters, and thus about 85 meters of gross head would be developed. Correspondingly, the Lower Tungnaa head would be 40 meters. Tailrace improvement along the small tributary might increase the Hrauneyjafoss head by a few meters. Route III would involve about 1.5 kilometers of tunneling and about 800 meters of tailrace canal excavation. Our field reconnaissance showed that most of the tributary valley and the proposed canal route is covered by superficial materials, probably overlying Palagonite, which locally may be at considerable depth. Tailrace canal excavation may, therefore, be relatively economical even though some portion might be in bedrock up to a total depth in the order of 20 to 25 meters. Route III permits either an underground powerstation or surface powerhouse. The length of the waterconductors for Routes II and III would be about the same regardless of which of the four damsites is selected.

Route IV returns the water to the River at a point on the bend of the River about 700 meters in direct line northerly from the Hrauneyjafoss waterfall. The tailwater level would be about 355 meters, thus 70 meters of gross head would be developed, leaving up to 55 meters for possible development by the Lower Tungnaa Project. We do not believe that any lesser development should be considered for Hrauneyjafoss. The length of the water conductors would be a minimum with a dam at Site D and would increase progressively proceeding to each upstream Site. The route is entirely in Palagonite. Either a surface or underground powerstation may be used. Selection of Route IV with Damsite D probably presents the least costly development for Hrauneyjafoss in terms of initial investment and unit power and energy costs, but may not represent the most economical development of the overall resource.

A surface powerhouse with either Routes III or IV may have individual penstocks either underground in shafts or tunnels or both, or on the surface with steel pipe on concrete supports. The choice would be on relative cost relationships which would be affected principally by subsurface geologic conditions. The Palagonite is, in general, adequately strong to support the concrete structures, including the surface powerhouse.

The geologic setting at the Hrauneyjafoss Project insofar as it relates in foundation investigations and planning studies for the power features in the Palagonite is, for all practical purposes, identical with the problems at the Tungnaarkrokur Project. Reference is made to our previous discussions in Chapter XIII for that Project. Our general recommendations for Tungnaarkrokur apply equally to Hrauneyjafoss. Based on inferences drawn from our observations of basalt breccia exposures of relatively good quality in the gorge walls downstream from the Hrauneyjafoss waterfall, the location of suitable rock for the underground features is indicated, but not assured, within the hill to the north.

Subsurface conditions for the rather long tailtunnel associated with either Route I or II are of major importance. There is the possibility that, with such a great length of excavation, there may be encountered zones of Palagonite which are so permeable and/or so weak structurally as to greatly increase costs or to make it impracticable to complete the Project without radical changes in plan. With either alignment, but particularly Route II, there is the additional hazard that in some places the roof may break through from the Palagonite into superficial material. The same hazard exists with Route I inasmuch as superficial material may be interbedded locally between the Palagonite and the Thjorsa lava. With the tailtunnel along Route I, if designed for free flow, the excavation will almost certainly cut, perhaps many times, the contact at the base of the Thjorsa lava. This contact is highly permeable and locally may be structurally weak, especially where the superficial materials might be encountered, and should be avoided. Lowering of the grade to produce a pressure tunnel and avoid this hazardous contact may be feasible but costly. These relationships mean that close-spaced exploratory drilling will be needed in the design phase along the selected tunnel route. Because of the variability of the Palagonite, the drilling will indicate only the general range of lithology and permeability in this area; it is not likely that the drill holes will chance to discover the worst material along the Route.

The selection of the Route for the power features from among the four alternatives can be accomplished properly only after extensive planning studies. These would include foundation investigations, some portion of which would need to be accomplished prior to the related office layout studies. For example, suitable rock for an underground powerstation would need to be located in order to position the related structures. These studies must also reflect the interrelation of the power features with the alternatives for the dam and spillway. Further, they must coordinate structurally the Hrauneyjafoss Project with the proposed Lower Tungnaa Project. It would be the aim of these planning studies, including field investigations, to evolve a Project Plan for Hrauneyjafoss. Additional design studies and associated detailed investigations would be the next logical step leading to ultimate construction.

WATER SUPPLY, POWER, AND ENERGY

The water supply available to the Hrauneyjafoss Project is essentially the same as that avilable to the Tungnaarkrokur Project, except that storage therefrom would not be available for regulation until the latter Project is built. The drainage area is only about four percent greater at the downstream plant. Flow correlation studies with the Thjorsa at Urridafoss, made by the SEA (9) show an estimated average annual unregulated flow at Hrauneyjafoss of 107 kl/s, which is nine kl/s greater than the similar estimate for Tungnaarkrokur. We note that this increase is over twice that of the drainage area relationship and thus should be checked. A more detailed discussion of flow records on the Tungnaa and storage utilization is presented in the discussion of the Tungnaarkrokur Project in Chapter XIII.

Hrauneyjafoss, on a power basis, represents additional head to that at Tungnaarkrokur. Accordingly, the station flow capacity should be approximately the same at each of the two plants and for each step in the development thereof. Full regulation of the Tungnaa at Hrauneyjafoss with diversion from the Thorisvatn-Kaldakvisl Project, but without the proposed diversion from Lake Langisjor, results in an average annual flow of about 154 kl/s, based on the SEA discharge estimates. This is about six percent more than for Tungnaarkrokur.

The ultimate installed flow capacity at Hrauneyjafoss with allowance for peaking capacity may be somewhat in excess of 210 kl/s. The corresponding ultimate installed power capacity will depend on the Route, among the alternatives discussed above, adopted for development. The possible range of installation may be about as follows:

Alternative	Ultimate Installed Capacity - KW
I or II	150,000 to 180,000
III	130,000 to 160,000
IV	100,000 to 130,000

System Operation Studies, discussed in Chapter I, will be required to establish the initial and the ultimate capacities at Hrauneyjafoss.

The gross average annual energy production at Hrauneyjafoss, based on the estimated fully regulated average annual discharge of 154 kl/s will amount to about 1050, 900, and 750 million kilowatthours, for development along Routes I or II, Route III, and Route IV, respectively. This energy production during years drier than average would be less unless offset by the release of hold-over storage in cyclic reservoirs located upstream.

FIELD INVESTIGATIONS

Topography

The existing 1:5000 scale topographic maps with some supplementing will be adequate for planning purposes. They should be extended to include the area along Route IV and downstream along the small tributary into which flow of that Route would discharge. The maps on a scale of 1:20,000 should be extended in the reservoir area to include the topographic divide on the lava plain to the east of Hrauneyjafell.

Maps on a scale of 1:1000 with one-meter contours will be required ultimately for the site of all structures selected for design, and for all construction material borrow areas. The detailed investigations may show the need for supplemental mapping of areas required for access roads, camps, etc.

Subsurface Investigations

The geologic complexities will require extensive subsurface investigations prior to and during the planning phase. Additional similar explorations will be essential in the design phase to develop detail at the site of proposed structures, especially those which may be located underground. The subsurface investigations will parallel closely those mentioned for the Tungnaarkrokur Project because of the great similarity in the geologic setting and development possibilities of the two Projects. Reference is made to our discussion and recommendations presented for that Project in Chapter XIII.

The problem of possible reservoir leakage through the Thjorsa lavas is perhaps less severe than at Tungnaarkrokur, but still important. Four churn drill holes should be drilled through the lava into the Palagonite equidistant along the dam axis. Permeability tests during drilling are required. In general, all holes drilled in the entire Project area should be preserved for watertable measurements. Inasmuch as we consider Site D somewhat more favorable than the other three alternatives, we suggest that the initial drilling be along this line. It will reveal the general stratigraphy of the lava plain, and the permeability tests will probably be generally representative of the area. These matters should be verified by not less than six additional holes located in the lava plain and positioned to give the most useful information regarding the groundwater table. This initial program may show the need for a few additional borings in the reservoir and damsite area in both the planning and design stages. Measurements of the direction and rate of movement of groundwater under the lava plain will be important.

Six borings should be made at the spillway and intake site in the planning phase, preferably at Site D. These may be diamond core drill holes and water pressure testing will be required. One hole should be drilled in each abutment, two in the riverbed area, and two at the intake site. They should all extend about fifteen meters below River level. One hole in each abutment at each of the other three alternative spillway sites would be desirable. Additional drilling during the design phase will be needed at the selected Site.

The geologic mapping and subsurface investigations required for the power features at Hrauneyjafoss will be basically the same as for Tungnaarkrokur, and our suggestions and recommendations should be followed here. Borings, and permeability tests thereof during drilling, at no greater than 500-meter centers along the tailtunnel alignments for Routes I and II and the canal for Route III will be necessary during the planning phase. Particular emphasis should be placed towards developing details of the geologic relationships referred to above. Careful drilling and testing will be required of the critical area where the alignment for Route I passes under the riverbed. Possible serious leakage during construction in this area might be averted by temporary diversion of the River into Hrauneyjakvisl. Additional investigations will be required in the design phase for the selected Route. This should include an exploratory tunnel similar to that recommended for Tungnaarkrokur.

CONSTRUCTION MATERIAL

Our comments and recommendations regarding construction materials for Tungnaarkrokur apply generally to Hrauneyjafoss. Material from the large gravel splay near Skeggjafoss may be suitable for processing into concrete aggregates or rockfill material. The old lake bed above Hrauneyjafoss may contain core material and fine aggregates. Again, better sources for the materials may be found in the old lake bed above Tungnaarkrokur, if that Project has not been built. The Thjorsa lavas may yield suitable material for concrete aggregates and rockfill. Generally, the investigations and tests should be accomplished for both Projects as though they were a single Project. This would include the planning of the access road.

CHAPTER XV

LOWER TUNGNAA PROJECT

GENERAL TOPOGRAPHY AND GEOLOGY

The Lower Tungnaa Project would be located on the Tungnaa River about nine kilometers upstream from its confluence with the Thjorsa River. The River elevation at the site is about 300 meters. The gross head to be developed would be between 25 and 55 meters, depending on its coordination with the Hrauneyjafoss Project, as discussed in Chapter XIV. Even with the minimum development at Hrauneyjafoss to tailwater elevation 355 meters, full head development at the Lower Tungnaa Project to that same level may not be justifiable economically.

The site extends between the mountain, Budarhals, on the right (north) side of the River and a Palagonite hill on the left (south) side, a distance of slightly more than one kilometer. Here again the Tungnaa flows along the edge of the Thjorsa lavas, which extend for 800 meters as a low level plain between the River and the Palagonite hill. At least one and possibly more Thjorsa flows are present. A map in the Kjartansson Report[2] shows the bedrock in Budarhals to be of the Hreppar Series. It was observed during our reconnaissance to be covered by a mantle of superficial materials, probably moraine and solifluction products. It is not now known to what extent the Hreppar rocks underlie the Thjorsa lavas to the south of the River. Doubless they would be separated therefrom by the superficial materials at the contact. Palagonite with a cover of superficial materials most certainly extends some distance under the lava and towards the River from the left abutment. No detailed geologic study has been made of the site.

No detailed topographic maps are available of the vicinity of the Project. Altitudes referred to above have been based on the 1:50,000 scale Army maps with 20-meter contours, which may be somewhat in error.

DEVELOPMENT ALTERNATIVES

No previous studies for development of the proposed Lower Tungnaa Project have, to our knowledge, been made.

The relatively flat gradient of the Tungnaa in the general reach does not permit economical head development by tunnels or canals. The head must be created entirely by a dam structure. The logical development would include a powerhouse with integral intake and a spillway, both constructed in the existing River channel, with fill dams extending to each abutment.

The bedrock of the Hreppar Series underlying the right abutment fill dam and probably extending under the proposed structures in the riverbed is expected to be of sound rock, adequate in strength and requiring relatively little foundation treatment.

The Thjorsa lavas which underlie the proposed fill dam east of the channel, while adequate in strength, will probably require a positive cut-off to bedrock. The contacts are expected to be highly permeable. The youngest of the Thjorsa flows in this area appears to terminate on the valley floor about two kilometers east of the Lower Tungnaa Site. There is a suggestion on the available aerial photographs that the flow which underlies most of the valley floor between the Palagonite hill and the River may terminate near the west end of the narrows, or may pass over or under the front of a flow which spread northward around the west side of the hill. These possibilities need checking in the field because, depending on distribution of the individual flows, it may be possible to locate the axis to reduce by one the number of contacts to be grouted under part or all of the structure. In any case, drill holes are needed along the axis to determine the number of flows present, and the general range of permeability of the contacts.

The aerial photographs indicate that the Palagonite hill forming the left abutment is part of a broad, low ridge which is continuous east to Hrauneyjafoss. There is thus no long seepage path through Thjorsa lavas associated with this Site. The hydraulic gradient through the ridge may, in places, be rather steep and geologic study and perhaps exploration by drilling as noted in our description of the Tungnaarkrokur Project will be needed.

WATER SUPPLY, POWER, AND ENERGY

An automatic, continuous water stage recorder was installed at Hald, three kilometers downstream from the Lower Tungnaa Project, in October 1959. This gage will ultimately provide useful water supply records for the proposed Project. Correlation studies made by the SEA [9] show an average annual discharge at Hald of 187 kl/s. The contributing drainage area, which includes the Kaldakvisl, is about 3470 square kilometers. The comparable flow estimate at Hrauneyjafoss with the Kaldakvisl-Thorisvatn diversion is 154 kl/s from a drainage area about 375 square kilometers less. The difference of 33 kl/s includes possibly on the order of ten kl/s leakage from Thorisvatn. However, the remainder, or 23 kl/s, appears to us to be slightly higher than might be expected from the residual drainage. Analyses of flow records as they become available from the new gages, plus occasional check measurements at other important points, such as Hrauneyjafoss, will in time permit a closer evaluation of the interrelation of discharge at various important points in the Tungnaa Basin.

The reservoir of the Lower Tungnaa Project to any proposed level will not provide any seasonal storage. Some pondage will be available, but with the lowest proposed level (325 meters) it may be so limited as to require an operation pattern almost identical with Hrauneyjafoss. Higher reservoir levels will increase the pondage rather considerably and permit some operational deviations if required. The return of Kaldakvisl-Thorisvatn storage to the Kaldakvisl instead of diversion to the Tungnaa would make the Lower Tungnaa Project the first reregulating reservoir downstream therefrom and may require a vastly different operational procedure at the latter plant, with a corresponding influence on installed capacities.

The capacity factor at the Lower Tungnaa Project with the aforementioned diversion into the Tungnaa, but not including the Langisjor diversion, may be somewhat less than at Hrauneyjafoss because of the lesser head involved, which tends to make peaking capacity relatively more expensive. However, the limited pondage and incremental flow would probably result in an installed flow capacity equal to or slightly greater than that at Hrauneyjafoss. The ultimate installed capacity, then, would be about 45,000, 70,000, and 100,000 kilowatts for reservoir levels of 325, 340, and 355, respectively. The initial installed capacity would be established by System Operation Studies and Planning Studies. The gross average annual energy production on the basis of the estimated flow of 187 kl/s, nearly fully regulated, would be on the order of 300, 500, and 700 million kilowatthours for the three reservoir levels, respectively.

Energy production in drier years would be reduced unless offset by hold-over storage in cyclic reservoirs such as Thorisvatn.

FIELD INVESTIGATIONS

The field investigations in the appraisal phase may be limited to only those necessary to adequately evaluate the Lower Tungnaa Project in its interrelation to the development of the Hrauneyjafoss Project. Inasmuch as the former will probably represent relatively high-cost power and energy, actual design and construction may be some years away.

The field investigations may be limited to some mapping and a few borings. The area of the damsite and reservoir should be mapped on the 1:20,000 scale with five-meter contours, and intermediate contours where necessary in flat portions. Any possible routes of long-path reservoir leakage revealed by geologic reconnaissance would also be similarly mapped. Four drill holes through the lava into the underlying rock should be accomplished. They should be positioned at equal intervals along the tentative axis of the left fill dam established after mapping and geologic reconnaissance. The first should be near the left water's edge. Permeability tests of all holes should be made during drilling. Geologic reconnaissance will determine whether borings are needed in the right abutment, riverbed, or elsewhere to supplement the drilling recommended above and establish an adequate basis for planning. Additional borings and detailed geologic studies will be required during the design phase of the Project.

Route studies for an access road will be desirable during the planning phase. Consideration should be given to a single route, which might extend from downstream and pass near the Project, extending on to serve the projects farther upstream.

A staff gage should be established at the site in order to develop a stage-discharge relationship.

CONSTRUCTION MATERIALS

Reconnaissance during the appraisal phase to locate possible sources of natural construction materials need only be carried out to the extent necessary to accomplish reasonably reliable cost estimates. Available materials would be similar to those for projects farther upstream and tests accomplished thereon would be generally indicative of suitability. The Thjorsa lavas present one source of rockfill and concrete aggregate materials probably suitable for processing. Basalt flows in the Hreppar Series of Budarhals may also be suitable for these purposes. A number of alluvial deposits nearby in the bed of the Tungnaa may yield suitable fine aggregates.

The nearest obvious supply of core material is the sediment of an ancient lava-dammed lake which is now part of the Thjorsa valley floor, about five kilometers west of the site. Perhaps loessic soils available on the southeast side of the Tungnaa near the site can be blended with the lacustrine sediments to make satisfactory core material.

CHAPTER XVI

UPPER TUNGNAA DEVELOPMENT

GENERAL TOPOGRAPHY AND GEOLOGY

The Upper Tungnaa as designated herein includes the Tungnaa River upstream from the Tungnaarkrokur Reservoir at elevation 500 meters, described in Chapter XIII, and the proposed diversion of Lake Langisjor.

The Tungnaa has its source at the ice fields of Vatnajokull at about elevation 700 meters and slightly higher, then flows southwesterly in a gently sloping valley for about 50 kilometers, dropping to an elevation of about 570 meters. It then turns north for about nine kilometers to Svartikrokur where it turns northwesterly, still maintaining a gentle grade, for about another five kilometers to the vicinity of Vatnaoldur at about elevation 560 meters. Downstream from Vatnaoldur the remainder of its course of about 48 kilometers is controlled by the Thjorsa lavas. It reaches the head of the Tungnaarkrokur Reservoir, at elevation 500 meters, eleven kilometers downstream from Vatnaoldur. In this reach, and downstream, it has the steep gradient with rapids and waterfalls characteristic of its course along the margin of the Thjorsa lavas. This latter reach has the potential for power development. Upstream from Vatnaoldur, only storage projects should be considered.

No major tributaries enter the Upper Tungnaa. Minor tributaries include the Vatnakvisl, entering at Svartikrokur, the Jokulgilskvisl entering near Nordurnamur, the Lonakvisl through which Lake Langisjor might be diverted, and a few lesser brooks.

The bedrock of nearly the entire drainage basin of the Upper Tungnaa belongs to the Palagonite Formation. Throughout some of the Basin, and particularly in the Vatnaoldur area, the Palagonite is covered with post-glacial pyroclastic material. The Thjorsa lava covers the lowlands on the left side of the River downstream from Vatnaoldur. No detailed geologic studies have been made of the Upper Tungnaa area.

The diversion of the Lake Langisjor, into the Upper Tungnaa was discussed by Kjartansson(2). It is a narrow and shallow Lake about 20 kilometers long extending southwest from Vatnajokull and paralleling the upper reaches of the Tungnaa at a distance of about eight kilometers to the southeast. It has an area of about 27 square kilometers, with the surface at about elevation 660 meters. The present outlet is easterly from near the northeast end of the Lake via the Utfall River to the Skafta River. It receives surface inflow from two streams extending only a very short distance from Vatnajokull; other surface drainage is very minor. Subsurface inflow from the Palagonite mountains which surround it can not be great. The entire bed of Langisjor is in Palagonite and there is some seepage from the Lake.

The area of the Upper Tungnaa is now covered only by the small-scale maps at scales of 1:100,000 and 1:50,000. Some of the area is now being mapped by the SEA on a scale of 1:20,000, and we also understand that soundings have recently been made of Langisjor.

Our field reconnaissance did not reach farther upstream than Vatnaoldur. The area is undeveloped and uninhabited and does not contain roads or trails. Permanent roads for construction and operation purposes will be relatively long and costly.

DEVELOPMENT POSSIBILITIES

We are in a position to present only very general recommendations and suggestions relative to the development of the Upper Tungnaa. More detailed studies must await completion of the mapping and also more detailed geologic information.

A possible power development at Bjallar was presented in a preliminary way by Thoroddsen[1]. Up to about 60 meters of gross head above elevation 505 meters might be developed. A relatively small amount of seasonal storage, about equivalent to that at Tungnaarkrokur, might be included. The proposed Project would involve a rockfill dam founded largely on the Thjorsa lavas, a spillway section in or near the existing riverbed, and power features in or passing through Palagonite on the right side of the River. The geologic relationships are thus very similar to those at

Tungnaarkrokur. Accordingly, the field investigations and planning procedures would be nearly identical, but aided by the experience which will have been gained at the projects located farther downstream.

Detailed studies should be deferred on the Bjallar Project for some time. Economic development is somewhat doubtful without seasonal storage located upstream. Water from the proposed Thorisvatn Storage would enter the Tungnaa downstream from the Site. It appears obvious that Bjallar would be substantially more costly on a unit basis than many other proposed Projects. Bjallar to a higher elevation than proposed above to develop a major storage reservoir may possibly be considered as an alternative to upstream storage developments if the latter prove to be high in cost or presents serious foundation problems.

Three sites, near Vatnaoldur, Ljotipollur, and Faxafit, for a dam to provide a major storage reservoir were mentioned by Thoroddsen(1). They appear on the small-scale maps to each present topographical conditions favorable for large storage development. The Vatnaoldur site, at about iver elevation 360 meters, was inspected by us. The foundation conditions were discouraging. The Site is located near the fissure from which presumably came the Thjorsa lavas. The entire area is covered, probably to great depth, by pyroclastic materials of extreme permeability. Even though some leakage is permissible inasmuch as it would reach downstream powerplants, the cost of foundation treatment to assure the safety of a dam at this Site may be prohibitive. Much detailed foundation information is necessary as a first step in any further consideration of Vatnaoldur. Geophysical surveys may be attempted initially.

The other two sites may, however, present the same problem in view of the reported predominance of these highly permeable volcanic materials along the Upper Tungnaa. The Ljotipollur Site, on the basis of the small-scale maps, could provide to elevation 590 meters possibly enough storage to permit full regulation of the Tungnaa. It is located about four kilometers downstream from the mouth of the Jokulgilskvisl, which rises at the Torfajokull ice cap. The main dam would be only about one kilometer long and not much more than 20 meters in height. An auxiliary dike might be needed at a low saddle located about three kilometers to the east. A similar site may be feasible at the constriction near Stori-Kylingur, on the Tungnaa upstream from the mouth of the Jokulgilskvisl. The apparent constriction near Faxafit, farther upstream, would be the uppermost site worthy of any consideration. The geologic relationships at these sites should be studied with a view to more detailed investigations of the one or ones involving dominantly Palagonite foundations.

Any consideration of storage development must be based on its utilization at all initial and/or ultimate Projects downstream on the Tungnaa and Thjorsa Rivers. The Thorisvatn-Tungnaa diversion may make it virtually unnecessary insofar as powerplants on the Tungnaa, other than

Bjallar, are concerned. However, ultimate development of the entire Thjorsa Basin appears to require the maximum feasible development of storage on the Upper Tungnaa. Also, provision of storage on the Upper Tungnaa may permit greater use of Thorisvatn for cyclic storage, enhacing the value of all storage thereby.

The development of the storage inherent at Lake Langisjor and its diversion into the Upper Tungnaa should be feasible. The possibility of the use of that storage at possible developments on the Skafta River has been outside the scope of our study. The rather full head development potential in the Tungnaa-Thjorsa downstream and located closer to load centers would, however, favor diversion thereinto. This development of Langisjor involves what appears to be a dam of relatively small magnitude at the outlet to provide storage by increasing the Lake level by ten to twenty meters. Diversion would require an intake and a tunnel, about three kilometers long, extending westerly to the Lonakvisl. The tunnel would be through Palagonite tuff and would probably require concrete lining and probably substantial support during construction. Some water problems during driving are to be expected, but should not be serious. Drilling at the damsite, south reservoir rim, and along the tunnel route would be required prior to design.

WATER SUPPLY, POWER AND ENERGY

An automatic continuous stage recorder was installed at Vatnaoldur in November 1958. Flow records therefrom are inadequate to present a reliable hydrological appraisal. Correlation studies made by the SEA[9] present an average annual discharge of 80 kl/s at this location. Similar correlations have not been made to our knowledge at the Site of any proposed upstream storage dams. They will be required for any such Site selected for further study and should be based in part on check measurements made at or near such Sites. The above flow without Langisjor diversion would have an annual yield of about 2500 million cubic meters. Storage to the extent feasible should probably not be less than 75 percent of this amount, or about 1900 million cubic meters. Storage reservoirs located farther upstream (other than Langisjor) would each require somewhat less volume for an equal degree of regulation because of less inflow.

Nearly full regulation of Lake Langisjor may be feasible. The storage volume with 20 meters depth of useful storage would be on the order of 500 million cubic meters. The outflow which may be largely saved for storage has not been reliably measured insofar as annual yield is concerned. Based on one known measurement, it may average 15 kl/s, which would be an annual yield of 470 million cubic meters. Because of the remote location, operation might involve fully opening the release at some time in the fall of the year with reregulation at the next storage reservoir downstream; and closing the outlet again at the beginning of the refill season in the spring. More hydrological information is required prior to planning and design.

If storage on the Upper Tungnaa above Bjallar is found not to be feasible, seasonal storage of about 200 million cubic meters at-site could nearly fully regulate the average flow of the River to an even flow, according to the monthly average flows at Vatnaoldur developed by the correlation study. The ultimate installed flow capacity at Bjallar with the Langisjor diversion and a relatively high capacity factor may be on the order of 135 kl/s, on the assumption that the at-site storage would be controlled for the primary benefit of that plant. The corresponding plant capacity with about 60 meters of maximum gross head and consideration of storage drawdown would be about 55,000 kilowatts. However, any storage on the Upper Tungnaa should be controlled for optimum System purposes, which may result in highly variable flow conditions at the Bjallar powerplant. This method of operation would greatly influence the ultimate installed capacity and the overall economics of Bjallar. It would have about the same position as an at-site powerplant for a major storage reservoir.

The gross average annual energy production at Bjallar from an average annual flow (including Langisjor) roughly estimated at 95 kl/s would be about 350 million kilowatthours, with some allowance for decreased head because of the use of seasonal storage. Lesser or greater heads than 60 meters would change these levels more or less in direct proportion. No power installation appears worthy of consideration elsewhere on the Upper Tungnaa.

Access to the Upper Tungnaa would represent an extension of the road to Tungnaarkrokur. Detailed route surveys and studies will be required sufficiently in advance of construction.

CONSTRUCTION MATERIALS

The comments relative to construction materials at the Tungnaarkrokur Project apply nearly equally to Bjallar and Vatnaoldur. However, the core deposits may be covered by waters of the reservoirs by the time Bjallar may be constructed. An alternative source would then need to be located.

Construction materials at any sites located farther upstream on the Tungnaa or at Langisjor will almost certainly present a problem. The Palagonite generally, and the Palagonite type, in particular, which dominates the Langisjor area, is not considered suitable for concrete aggregate or rockfill construction. We know of no post-glacial lava other than the Thjorsa lavas. Moraine material may be suitable for rolled filled construction. The pyroclastic materials are probably only suitable for road metal. Inasmuch as suitable construction material may only be available from distances requiring a long haul, the geologic reconnaissance in the vicinity of the sites must be exceptionally thorough.

CHAPTER XVII

BURFELL AND SULTARTANGI PROJECTS

GENERAL TOPOGRAPHY AND GEOLOGY

The proposed power developments at Burfell and Sultartangi represent alternative plans for utilizing approximately the same head and water. Either development would be relatively large compared with other single developments proposed on the Thjorsa-Hvita River Systems. The Sultartangi Project has been studied by Thoroddsen [(1)], but the Burfell Project as proposed herein has not been investigated previously.

The Sultartangi Project involves diversion of the Thjorsa River by a low dam near the mouth of the Tungnaa and a tunnel extending westward through the mountains, Saudafell and Stangarfjall, to the Fossa River. The Fossa River parallels the Thjorsa and joins it near the mountain, Burfell. The Thjorsa water would enter the Fossa about five kilometers downstream from the waterfall, Haifoss. The gross head to be developed would amount to about 130 meters. The plan of the Project is shown on Thoroddsen's Drawings A-1536, 37, and 38, and is not duplicated on Exhibit 13.

The Sultartangi Dam as proposed would create a reservoir to elevation 290 meters with daily pondage but no seasonal storage. The dam would be founded entirely on Thjorsa lavas except at the right abutment. The maximum height would be about 20 meters where it crosses the channel of the Thjorsa River; through most of its length of about 3.7 kilometers to the Palagonite mountain, Valafell, it would be less than ten meters high. In view of the relatively low head it is possible that leakage may be within acceptable limits without foundation treatment. But the relatively large discharge of the Ytri-Ranga River, formed by springs which issue from the Thjorsa lava about 15 kilometers downstream from the site, indicate the high degree of permeability that is to be anticipated. The fact that a drill hole near the site, intended for placement of a recording gage, found the watertable in the lava at the River's edge to be below the River level, indicates that the River channel has been partially sealed by silting and that the groundwater moves freely down-valley on a slope at lower elevation than that of the River. Much of the floor of the reservoir near the dam will be the bare surface of the lava. There is therefore a real danger that leakage may be excessive, and that the velocity of flow, particularly along the short path to the River channel immediately downstream from the dam, may be such that natural sealing will not occur or will be long delayed.

The right (northwest) abutment of the dam would be in the Hreppar Series overlain by superficial material, and should present no serious foundation problems.

Reconnaissance by Kjartansson[2] indicated that the tunnel would lie chiefly in solid basalt and interbedded sediments comprising the Hreppar Series, and that it would be in or near a body of intrusive rhyolite near the west end. The tunnel and powerhouse excavations would be entirely below the watertable; the headrace tunnel passing beneath the channel of the Räuda River. Because a single block of bad ground anywhere along the eight-kilometer length of the tunnel could enormously increase its cost, it is essential that the route be investigated by detailed geologic mapping of the surface and sufficient drilling to ascertain the rocks that will be encountered. It will be necessary to depend largely on drilling because much of the surface is mantled by superficial materials.

Exposures of rhyolite described by Kjartansson on the east side of the Fossa were not accessible at the time of our reconnaissance; the rhyolite was seen only on the west side of the River opposite the powerhouse site. Most exposures show a greater or lesser degree of hydrothermal alteration, the effect of which is to soften the rock. Where the west valley side consists in part of altered rhyolite it is a steep cliff, clearly formed by landsliding, and bordered at the base by a jumble of slide debris. Slides on a smaller scale occur in the vicinity of the rhyolite exposures on the east valley side. The landsliding, and the fact that altered rhyolite is notorious as tunnel rock because of its tendency to flow plastically, mean that drilling is needed to determine the condition of this rock where it is cut by the underground excavations. If its condition is at all questionable, it will be necessary to change the alignment of the structures.

The Thjorsa River falls about 90 meters over a series of rapids and waterfalls from the low gradient upstream from the waterfall, Trollkonufoss, east of Burfell, to where it resumes the low gradient about one kilometer upstream from the mouth of the Fossa. At this downstream point, the water level is about 121 meters. The River in this reach of about eight kilometers nearly reverses its direction as it flows around the mountain, Burfell.

The River flows on the Thjorsa lavas for many kilometers until it reaches its confluence with the Bjarnalaekur at the south end of Burfell. Downstream therefrom it has carved its channel into rocks of the Hreppar Series. The Thjorsa lava flowed through a two-kilometer wide gap between Burfell and the volcanic breccia slopes on the east to debouch on the plain to the southwest. Two smaller rivers, the Ytri-Ranga on the east and the Bjarnalaekur on the west, have developed along the margin of the lavas to grades generally below that of the Thjorsa. Their flow comes largely from springs issuing from the lava. The Ytri-Ranga flows directly to the ocean, while the Bjarnalaekur is intercepted by the Thjorsa.

The Thjorsa lava in the vicinity of Burfell and for several kilometers upstream is covered, except in the River channel, by a sheet of layered ash and loessic soil which may be several meters thick.

Burfell has not been studied geologically, but appears to consist of basalt flows with interbedded sedimentary units probably belonging to the Hreppar Series. Both the flows and the sediments are dense, strong rocks that should present no special problems.

The natural fall of about 90 meters potential of development may be supplemented by a dam located a short distance upstream of Trollkonufoss. The dam should probably not be to a reservoir level below 235 meters, and might extend as high as elevation 300 meters, about the tailwater level of both the Lower Tungnaa Project and a feasible site on the Upper Thjorsa. The gross head to be developed, then, may range from 114 to 179 meters.

A low auxiliary dam would be required for any reservoir level higher than about 235 meters to close a gap in the west reservoir rim between Skeljafell and Stangarfjall, and through which flows the Rauda River. The location is indicated on Exhibit 13. This gap contains a tongue of Thjorsa lava which spreads westward into the Fossa Valley. The underlying bedrock belongs to the Hreppar Series.

The area of both the Sultartangi and Burfell alternative Projects has not been mapped to large scale. The general altitudes referred to above have been taken from the 1:50,000 scale Army maps and the 1:100,000 Danish Geodetic maps. They may be somewhat in error. No useful information appears to be available from studies made near Burfell over 30 years ago by a Norwegian hydroelectric engineer. Aerial photographs of both areas and the profile of the River are available.

The Burfell area is accessible by a trail from the end of the road ten kilometers to the southwest. The area of the Sultartangi Project is difficult of access even by the track from the west. Both areas are uninhabited.

DEVELOPMENT ALTERNATIVES

Burfell Project

The development of the Burfell Project is rather clearly indicated geologically and topographically. As shown on Exhibit 13, it would consist of: (1) a concrete overflow spillway with rockfill dams extending to each abutment, (2) a rockfill reservoir rim dam in the Rauda Gap, (3) a reservoir, (4) a concrete intake structure connecting to (5) tunnel water conductors extending westerly through Burfell to tailwater about one kilometer upstream of the mouth of the Fossa, and (6) a powerhouse.

The spillway would probably be located in or adjacent to the present River channel a short distance upstream of the waterfall, Trollkonufoss. Alternative locations might be in the channel of either of the two lava-margin streams if a simpler diversion and final River closure problem would reduce overall costs. The Thjorsa location appears preferable and may have a simpler energy dissipation problem. The structures would be founded in adequately strong Thjorsa lava--a location in the channel of the Ytri-Ranga may involve inadequate foundations of volcanic breccia. Spillway gates would probably prove less costly than the increased dam height required for an uncontrolled spillway.

Rockfill dams with an impervious core would extend to either abutment, a total distance of about two kilometers. Stripping of the ash and soil cover down to bedrock will be required. The foundation rock of lava, basalt, or volcanic breccia should be adequately strong to support a dam of maximum height--to reservoir elevation 300 meters. The Thjorsa channel is about five meters lower and the Ytri-Ranga channel about ten meters lower than the general level of the lava plain. Except at the abutments the dam will be entirely on the Thjorsa lava and the large size of the springs discharging into the Ytri-Ranga just above the site, together with the steep hydraulic gradient downstream, indicate that any preliminary estimate of cost should provide for a grout curtain in at least one interflow contact under the full length of the dam and spillway. The left abutment was not accessible at the time of our examination, but it apparently consists of volcanic breccia and will probably need considerable grouting. The right abutment, which is the base of Burfell, appears to be sound basalt.

If other factors permit, it may be advisable to develop Burfell in stages, first with a low dam to, for example, elevation 235 meters to provide (a), a test of the tightness of the reservoir, and (b), an opportunity for natural sealing by River silt under low-head reservoir operation. Whether the ash and loessic soil overlying much of the bedrock upstream from the dam is sufficiently impermeable to operate as a blanket is not known, but it will certainly serve as a screen that will be quickly sealed by a slurry of silt and clay deposited on the reservoir floor. Whether it will be economic to take steps to accelerate the natural sealing, and if so, whether this can be accomplished best by further grouting at specific places, or by blanketing of specific intake areas, can best be determined by study of actual leakage paths with the reservoir in operation.

The thickness of the Thjorsa lava flow in the Räuda Gap, and the permeability of its base, must be investigated by drilling. Grouting of this contact will very likely be required for a reservoir level in excess of about 235 meters, but not for a lesser level. Higher levels will also require a rockfill dam with impervious core.

It is important to note that, at the 240-meter level, the channel of the Thjorsa is very nearly flush with the surface of the lava flow which forms the valley floor, and that the western part of the valley floor is drained westward by the Rauda River via the Rauda Gap; the divide between the Thjorsa and Rauda is on the nearly flat valley floor a little above or a little below elevation 240 meters. The backwater effect of a 240-meter reservoir will cause a decrease in the velocity of the Thjorsa and a deposition of sediment in its channel for a considerable distance up-valley from the head of the reservoir and it may be anticipated that the shifting of the River on its deltaic plain could cause it to spill across the divide through the Rauda rather soon, perhaps within a few years after the reservoir is in operation. Thus, even though the Thjorsa-Rauda divide may be somewhat above 240 meters, there may be need for the auxiliary dam in the Rauda Gap at the outset, and this dam should have a freeboard of about five meters to allow for the gradient of the Thjorsa on its delta.

The initial and the ultimate reservoir level at the Burfell Project will be established by detailed planning and design studies. Stage development, referred to above, may also be desirable for economic reasons, and the initial structures may therefore provide for future raising. Ultimate development of the total resource up to elevation 300 meters may never be justifiable economically and some sacrifice of head and storage may be essential. The economic height may not exceed about elevation 260 meters. At that height, the volume of fill material required for the dams is on the order of 10,000,000 cubic meters.

It is probable that some seasonal storage may be provided economically in the reservoir. Its cost, after consideration of the value of at-site power and energy, should be comparable with alternative storage located farther upstream. The justifiable storage may range somewhere between the 150 million cubic meters which can be provided with a ten-meter drawdown below elevation 240 meters to the 1000 million cubic meters available with a 20-meter drawdown below elevation 260 meters. As a minimum, pondage to regulate natural and regulated flows should be provided.

The concrete intake structure would be founded on sound basalt on the east side of Burfell and close to the dam. Ice problems must be considered in the design. The deepest feasible level without special approach channels is desirable. Consideration must be given to possible future increases in capacity and in head.

The tunnels extending from the intake to tailwater would pass through Burfell for a distance of about 2.5 kilometers. Tunneling conditions in the rock are expected to be favorable. Support during driving should not be extensive. Concrete lining of pressure conduits and possibly also any excavated surge tanks would be desirable and is recommended. Tail-tunnels, if used, should require lining only through occasional structurally weak zones.

On the west side of the Fossa valley a sheet of pillow-palagonite breccia is interbedded with the Hreppar sequence; similar breccia sheets may occur in Burfell. In any case, detailed geologic mapping and drilling will be needed to determine the most favorable position for the Burfell tunnels. Fault or fracture zones readily seen on the airphotos are probably more permeable than the adjoining rock and should be avoided insofar as feasible.

Rock conditions for an underground powerstation are expected to be favorable. A headtunnel type of development placing the powerstation as far downstream as feasible would tend to reduce water problems. Pen-stocks directly connecting the intake to the spiral cases, followed by a long tailtunnel may, however, be feasible and more economical. A surface powerhouse served by penstocks, either in tunnels or on the surface, is entirely feasible and should be studied. It may present advantages with respect to future enlargement.

A saddle at about elevation 260 meters at the northwest base of Burfell leads itself to a number of short tunnel-canal-penstock combinations, which may be economically competitive with the tunnel schemes for high reservoir levels. One such scheme is indicated on Exhibit 13. This alternative may be studied in the planning phase.

Sultartangi Project

The alternative Sultartangi Project, briefly described above, is more fully covered by the Thoroddsen Report [1]. After adequate field information becomes available, the two proposed Projects should be studied on a comparable basis as a guide for selection between the two. It is our present opinion that the Burfell Project is overall the more favorable.

WATER SUPPLY, POWER, AND ENERGY

An automatic continuous stage recorder was installed at Trollkonuhlap, near the proposed Burfell damsite, in the autumn of 1959. The drainage area at the gage is 6380 square kilometers, which is 60 square kilometers more than at Sultartangi, near the confluence of the Tungnaa and Upper Thjorsa. Records from this new gage will progressively permit a reasonably accurate correlation with the longer-term record at Urridafoss, where the drainage area is only about thirteen percent greater.

Correlation studies made by the SEA [9] with the Urridafoss record show an average annual discharge of the Thjorsa at Sultartangi of 334 kl/s. The discharge at Burfell, where the drainage area is less than one percent greater, may be about the same when consideration is given to possible leakage losses to the Ytri-Ranga. The flow of that stream could be saved for power with a dam at Burfell, and discharge measurements of that stream at the site as well as of the Bjarnalaekur should be made.

The SEA correlation study showed that the flows of the Thjorsa at Sultartangi tend to be low except during the summer months from May through August. The general flow pattern should be very similar to that at Urridafoss. The average monthly discharges from the study indicate that 1800 million cubic meters of storage would be required to achieve a uniform flow throughout an average year. Use of hold-over storage during years drier than average would add further to at-site and upstream storage requirements. It is therefore evident that seasonal storage located upstream, additionally to that at Thorisvatn, will ultimately be required.

It appears reasonable to assume that the ultimate installed flow capacity at Burfell should be based on the average annual discharge at a plant capacity factor of 50 percent or less, or about 670 kl/s. The similar installation at the alternative Sultartangi Project might be less because of the cost penalty of the long tunnel. Incremental peaking capacity should be substantially less costly at Burfell with the shorter tunnel. The corresponding power capability at Burfell would be dependent on the ultimate reservoir level. It could range from about 600,000 kilowatts for a 235-meter pool to about 900,000 kilowatts for a 300-meter pool with some allowance for storage drawdown. The comparable ultimate installed capacity of the alternative Sultartangi Project would be about

650,000 kilowatts, with the Thoroddsen plan of development modified to a flow capacity of 670 kl/s. The gross average annual energy production from a regulated flow of 334 kl/s at Burfell would range from about 2500 million kilowatthours for a 235-meter pool to about 4000 million kilowatthours a 300-meter pool with storage. Comparable energy production at Sultartangi would be about 2900 million kilowatthours..

The initial installed flow capacity at the selected plant should probably not be less than the average annual flow, and possibly somewhat greater, providing of course, that load is available. A rather large load increment would appear to be required to justify such a large Project. Its size would also involve flow regulation by storage necessary either at the time of construction or shortly thereafter, unless previously installed.

FIELD INVESTIGATIONS

The field investigations should be conducted in three phases. The first would go only so far as needed to permit the selection between the alternatives, Burfell and Sultartangi. The second phase would permit detailed planning of the selected Project. Finally, additional investigations basic to detailed design and construction would be required.

Mapping required for the first phase would involve topography on a scale of 1:20,000 with five-meter contours in the general area of proposed structures at both Projects including their reservoir areas. Additional similar topography along tunnel routes may be essential for the geologic mapping referred to above. The project planning phase should not require additional topographic mapping. Detailed mapping of the sites of all structures selected for design will be necessary ultimately. A scale of 1:1000 with one-meter contours is suggested.

General geologic reconnaissance and stratigraphic mapping is required in the initial phase for both Projects. Special attention is required for the Sultartangi long-tunnel route where intrusive rhyolite may be encountered. This may result in a different route to miss this bedrock. Geologic studies would continue through the subsequent engineering phases of the selected Project.

Subsurface borings are necessary for the initial phase. The drilling at the two alternative damsites would be very similar. A minimum of eight borings at each site is recommended. They should be more or less equally spaced, drilled into the bedrock underlying the Thjorsa lava (when present), and given permeability tests during drilling. All holes should be preserved for watertable measurements. Churn drilling is recommended. Diamond drilling may be more satisfactory for borings in the Hreppar Series. One hole at each of the tunnel adits of each Project should be included in the initial phase. At least one hole should be drilled through the Thjorsa lava at the Rauda Gap. Several drill holes may be required to give reasonable assurance that the Sultartangi tunnel will miss the intrusive rhyolite. The probable number cannot be established without additional geologic study and some actual drilling.

Additional drilling will, of course, be required in the project planning and design phases to develop details of subsurface conditions at the site of selected structures. This is especially necessary for proposed underground structures. Observation wells to permit study of the level and movement of groundwater especially in the vicinity of the dam on the Thjorsa lava will be a part of the project planning phase and accomplished in the same general manner as outlined in Chapter XIII for the Tungnaarkrokur Project.

The depth and character of the soil mantle on the Thjorsa lava at Burfell must be investigated by test pits or bulldozer trenches. Laboratory tests will be needed. Field permeability tests should also provide important information.

A staff gage is needed at each proposed damsite and tailwater point with enough readings made to establish stage-discharge relationships. Additional hydraulic surveys and studies will almost certainly be required to establish this relationship through the expected discharge range on the Fossa River at the tailwater from the Sultartangi Project.

Route surveys and studies for the access road may be required in the initial phase of the investigations for the power end of both Projects, but should not be important for the damsites of either alternative prior to project planning. Permanent access along the east side of the River would extend on to other Projects located farther upstream.

CONSTRUCTION MATERIALS

Rockfill shell and filter material and concrete aggregates can be manufactured from Thjorsa lavas or basalt of the Hreppar Series. Some or all of the tunnel spoil may also be satisfactory. No gravel deposits were observed in the general area and their presence is improbable. Alluvial islands in the bed of the Thjorsa may present a satisfactory source for fine aggregate.

The alluvium-floored embayment drained by the Rauda River just east of Stangarfjall is clearly a filled lava-margin lake, and it will probably yield core material for dams. Laboratory investigations are needed to determine whether the pumice-rich loessic soils at the Burfell site can be blended with material from the Rauda embayment, or sufficiently compacted by special methods of placement, to be usable in the cores of the embankments.

CHAPTER XVIII

OTHER PROJECTS

GENERAL

There are potential projects, other than the ones discussed in the preceding Chapters, which should be studied as a part of the overall development of the Hvita and Thjorsa River Basins for hydroelectric power. In general, they are projects with somewhat smaller power potential. Most have had the benefit of some previous study. Our discussion which follows does not include any of the very small projects up to, say, 5000 kilowatts capacity which may exist in relative abundance on the smaller tributaries of the two Rivers. We have also not included any further discussion of projects on the two main Rivers which may develop some of the head sacrified by the more major and obviously more attractive projects presented in the preceding Chapters. Each Project upon which we have made some general, but usually minor, study is discussed individually.

APAVATN STORAGE AND DYNJANDI POWER PROJECT

The possibility of developing Lake Apavatn as a seasonal storage reservoir was referred to in Chapter V. The present surface area of Apavatn is fourteen square kilometers. It drains for about one kilometer through the Hagaos to the Bruara River. The Hagaos also drains Lake Laugarvatn, located about two kilometers northwest of Apavatn but with a level 2.6 meters higher. The normal level of Apavatn is about 59 meters.

The average annual discharge of the Hagaos River is not known. Records are available for the Bruara at Dynjandi since August 1948 and show an average discharge of 66 kl/s. The Bruara is a linda river and the flows are moderately uniform. The same should be true of the Hagaos. The drainage area at Dynjandi is 670 square kilometers, of which possibly on the order of one-fourth may be represented by the Hagaos. On the assumption of discharge varying directly with drainage area, the average discharge of the Hagaos would be about 16 kl/s which would yield about 500 million cubic meters annually.

Storage may be attained by either increasing or decreasing, or both, the level of Lake Apavatn. The area was not visited during our reconnaissance. No large-scale topography, or hydrographic surveys are available. The available small-scale topography indicates that the area adjacent to the Lake is fairly level and up to only a few meters above its normal level. Grazing land occupied by several low-lying farmsteads appears to extend to the Lake boundary. Raising of Apavatn to provide storage would result in some cultural damages, and should possibly be limited to only one or two meters. Thoroddsen[1] proposed a raising of one meter, to elevation 60 meters, with the Dynjandi Project.

The lack of hydrographic surveys of the Lake and the beds of the Hagaos and Bruara downstream does not permit an evaluation at this time of the storage volume which may be achieved by the lowering of Apavatn. These data as well as large scale (1:10,000 with 0.5-meter contours) topography adjacent to Apavatn should be obtained. Some dredging of the outlet or providing a new outlet may permit up to five meters of storage by lowering of Apavatn, and without any apparent cultural damage.

The potential seasonal storage in Apavatn may be in excess of 50 but less than 100 million cubic meters. This storage would be operated for optimum system benefit by enhancement of the energy production at such downstream plants as Hestvatn and Selfoss. Control of releases would be necessary but the most favorable location and design of the control works must await the additional field investigations. It is probable that a dam at Dynjandi is the preferred location, and could be designed to provide either initial or future power installation. This location would have the great advantage of controlling the Bruara River instead of the much smaller Hagaos tributary.

The development of the Bruara River at the Dynjandi Rapids has been proposed by Thoroddsen[1]. The plan of development and the local topography is shown on his Drawing A-1777. Ten meters of head between elevations 50 and 60 meters would be utilized for power, and the average annual energy production would be about 40 million kilowatthours. The development of additional head at this Site does not appear feasible unless the level of Apavatn may be increased over 60 meters. There may be some slight backwater effect at times from the Hestvatn Project on Dynjandi tailwater.

The reservoir for Dynjandi to elevation 59 meters or higher and with some improvement of outlet conditions at Apavatn would represent the Apavatn Storage Project discussed above. The release of inflow and storage would alter the existing flow pattern downstream in the River from the natural conditions and to a degree somewhat dependent on the storage created. Releases may be on the order of 100 kl/s if the storage is about 50 million cubic meters. The flow capacity of a power unit when installed at Dynjandi may be about that amount, and the rating would be on the order of 7000 kilowatts. The greater capacity of downstream plants means that the Dynjandi Power Project would have only a minor influence on release rates, and outflow required downstream would need to be passed.

The basic Project Layout shown by Thoroddsen's drawing appears generally satisfactory. Foundation exploration and geologic study is required to develop the Project Plan. Alternative arrangements and details of principal features require more study and evaluation. For example, tainter or fish-belly flap gates may be much less costly than hook gates as now proposed. Consideration should be given to operating this single-unit installation by remote control from a nearby plant such as the Hestvatn Project. Natural construction materials should present no special problem in that area.

Inasmuch as the Apavatn storage may be justified by the requirements of a downstream plant or plants, it may be that power costs will be based primarily on the cost of the direct power facilities plus some reasonable allowance of the cost of the common features such as reservoir, dam, and spillway. The unit power and energy costs may be very attractive on that basis. We recommend that the Dynjandi Project to include Apavatn Storage be considered for possible construction at the same time or soon after the completion of the Hestvatn Project.

VORDUFELL PUMPED STORAGE

The natural lake near the crest of Vordufell presents attractive possibilities for pumped storage development. It is located about seven kilometers northeast of Hestvatn. A small canal, less than one kilometer long could provide a water supply from the Hvita (Hestvatn Reservoir) to a reversible pump-turbine power and pumping station located at the foot of the mountain, Vordufell. A pressure water conductor extending to the lake will be slightly more than one kilometer long. The potential gross head is between 260 and 270 meters. The natural lake may be of adequate size; if not, enlargement may not be costly.

The development of the Vordufell Project may present an economic source of peaking capacity which should be compared with the cost of incremental capacity at other projects, such as Gullfoss. Off-peak energy would be used to pump water to the high-level lake for release through the pump-turbine to create power at the time of system peaks. An approximate analysis made with no additional field information other than may be provided by general reconnaissance should establish the approximate level of the costs of peaking capacity. Additional detailed investigations and studies may follow this approximation if the capacity costs are comparable with incremented capacity at alternative projects.

VATNSLEYSUFOSS PROJECT

The Vatnsleysufoss Project would be located on the Tungfljot River, about ten kilometers upstream from its confluence with the Hvita River. The tailwater level at this point would be about 56 meters, and should be beyond any appreciable backwater from the Hestvatn Project. Development of any remaining head downstream to Hestvatn does not appear justified. Also, a project on the Hvita towards the upper end of the Hestvatn backwater and which would extend up the Tungfljot does not appear worthy of consideration.

The fall between the top of the waterfall, Vatnsleysufoss, and the rapids extending for one kilometer downstream to the tailwater point referred to above is about eleven meters. The site of a diversion dam at or near the falls is not favorable in that a dam to gain additional head and provide adequate submergence for the power intake would need to be very long. The riverbed upstream from the falls is carved into the basalt bedrock only about two or three meters. The area of Vatnsleysufoss was inspected during our field reconnaissance.

There is an additional natural fall of about nineteen meters up to elevation 86 meters in the 3.8 kilometers of River immediately upstream from the Vatnsleysufoss waterfall. About thirteen meters of this drop are concentrated in a rapids about 800 meters long at the upper end of this reach while the remainder is represented by a uniform gradient in the intervening three kilometers of river.

The topography and cultural development (farmsteads and grazing), on the basis of the small-scale maps, appears to limit the reservoir elevation of a dam located at the upstream end of this reach to about elevation 96 meters. There is thus a gross head of about 40 meters which may be developed in the river distance of about five kilometers discussed above. The diversion dam would be located at or near the upper end of this reach. The reservoir to elevation 96 meters would extend through a relatively flat gradient reach of the Tungufljot for about eight kilometers upstream, or about one kilometer beyond the mouth of the Kjosastadulekur Brook. The volume therein should permit adequate daily pondage. The dam would be a gated concrete structure, though a portion of the design spillway capacity may be provided by an uncontrolled overflow section. Ice control features would be incorporated in the structure with the power intake adjacent thereto. It is probable that the normal reservoir level should be such as not to require any auxiliary dikes beyond the main spillway abutments.

The powerstation should be located underground and near enough to the intake to be served directly by an individual penstock to each unit. A tailtunnel would extend downstream on the right (west) side of the River to tailwater at about elevation 56 meters, and would be about 4.5 kilometers long. The topography does not permit a headtunnel type of development. The bedrock appears to consist of the Grey Basalt Formation and should not present any serious foundation problems.

Project planning investigations and studies will be required to more clearly establish the proposed Vatnsleysufoss Project. The general plan outlined above represents our present concept only and is based on rather limited data. Large-scale topography, geologic reconnaissance, and foundation exploration will be required prior to more detailed planning. Natural construction materials located nearby should also present no special problem.

The water supply available to the Vatnsleysufoss Project will require special study. The possible diversion to the Hvita of that portion of the flow of the Tungufljot which originates upstream of the outlets from Sandvatn was discussed in Chapter VIII. Conversely, the possible diversion of the Hvita to the Tungufljot and entering at the upper end of the Vatnsleysufoss Reservoir was also discussed therein. Either or both diversions might be feasible and have a very important bearing on the power installation at the Vatnsleysufoss Project.

The diversion of the Tungufljot from Sandvatn to the Hvita would seriously affect any power development on the former River of the available head of about 175 meters between Sandvatn and the proposed Vatnsleysufoss Project. On the other hand, the diverted water could be used for power through about the same total head on Projects located on the Hvita upstream of the mouth of the Tungufljot. The incremental inflow on the Tungufljot with diversion at Sandvatn could probably not be used for power within the reach of its origin inasmuch as the flow may be too small to justify power development. We have not made any specific studies relative to power development by a project or projects located on the Tungufljot between Sandvatn and the Vatnsleysufoss Project either with or without Sandvatn diversion to the Hvita. However, such potential development may need to be studied prior to any final decision relative to Sandvatn Diversion to the Hvita or Hvita diversion to the Tungufljot, and on the basis of more hydrologic, topographic, and geologic information than presently available.

The SEA river profile and small-scale maps show a steep gradient on the Tungufljot immediately upstream from the head of the Vatnsleysufoss

Reservoir. There appears to be a total fall of about 110 meters in the first 6.5 kilometers, but beyond, for about twelve kilometers to Sandvatn, the gradient flattens to average about 5.8 meters per kilometer which is only about one-third that of the lower portion. The overall course is fairly straight. It may be that power development of some portion of the lower 110 meters of fall may be feasible if Sandvatn is not diverted to the Hvita. The general flatness of the countryside beyond does not permit much additional head concentrated at a dam.

The average discharge of the Tungufljot at the gage located very near Vatnsleysufoss since August 1951 is 47 kl/s according to the SEA report[9]. It is a linda river and the flow is moderately uniform varying from 36 to 71 kl/s on the basis of the published monthly averages. The highest flood peak was 98 kl/s in the winter of 1952-53. There does not appear to be any feasible storage reservoir on the Tungufljot unless Sandvatn is feasible of control. This possibility should be studied. A station flow capacity of 70 kl/s would, on the basis of the published duration curve, permit energy production at the Vatnsleysufoss Project from nearly all of the available flow, and at a moderately high capacity factor. No diversion from or into the Tungufljot is assumed. The installed capacity on this flow basis and for the development of the Vatnsleysufoss Project as proposed above would be about 20,000 kilowatts. We suggest an installation of two units remotely operated from another plant, such as Hestvatn. The average gross annual energy production from this proposed development would be about 120 million kilowatthours.

SELFOSS PROJECT

The Selfoss Project would utilize for power and energy the flow of the Olfusa River (the name applied to the continuation of the Hvita after its confluence with the Sog) at the waterfall, Selfoss, near the town of the same name. The head available is about seven meters. The average annual discharge from the records of the gage established at that point in September 1950 is 386 kl/s. The vicinity of the Project was visited several times during our field reconnaissance.

A plan of development for this Project has been briefly presented by Thoroddsen(1) and the general details are presented on his drawing A-1781. We are, at present, in agreement with the basic engineering features of his plan of development. Additional field investigations and planning studies will be required to select a definite project plan. Consideration would need to be given to the possible regulation from Hvitarvatn and Apavatn, and may show that the installed flow capacity may be somewhat greater than the 330 kl/s proposed by Thoroddsen. We suggest that a station flow capacity about equal to the average flow be used for appraisal purposes, but the optimum capacity would need to be established by detailed economic analyses. Three generating units rather than two may be more economical and desirable, and would permit one unit to be out of service for maintenance during low-flow periods with little energy loss. The turbines should be of the Kaplan type in view of the capacity-head reduction during the high-flow periods.

A fixed headwater elevation for nearly all flows will be required because of cultural requirements in the town of Selfoss, some of which were referred to by Thoroddsen. The headwater level may need to be somewhat less than fourteen meters with a corresponding reduction in developed head. The spillway would be a low concrete sill surmounted by gates and piers. Tainter gates or fish-belly flap gates are almost certainly less costly than hook gates for control purposes.

Extensive field investigations will be required prior to more detailed planning. The bedrock of the entire area is the Thjorsa lavas and considerable drilling will be required in order to plan and estimate the foundation treatment which may need to be extensive in order to reduce expected leakage. Hydraulic data will be required to permit the computation of backwater curves to beyond important cultural developments. Hydrographic surveys will be required at the site of all permanent structures and diversion works located in the riverbed. Accurate and detailed surveys will be required of all cultural developments which may be affected such as houses, sewers, and water lines, including hot-water facilities. A location for the dam upstream from the town might be considered.

The inherent high unit costs involved with such a low-head development as Selfoss can hardly be offset by the relatively high and uniform flow available. It is our present opinion, therefore, that the probable unit power and energy costs will be so high compared with many alternative developments that the Selfoss Project may not be justified for many years.

SKARD PROJECT

About 55 meters of fall on the Thjorsa River are available for possible power development from the tailwater of the proposed Burfell Project at elevation 121 meters to the foot of the waterfall, Budafoss, 26 kilometers upstream from the highway bridge at Urridafoss. The length of the reach is about 26 kilometers. Budafoss is a near vertical drop of about seven meters. Another 14 meters, below elevation 99 meters, is concentrated in the one-kilometer long Skard Rapids located about five kilometers upstream of Budafoss. The gradient between is uniform with a total drop of about twelve meters not including Budafoss. The remaining fall of 22 meters is on a near uniform gradient in the 19.5 kilometer reach between Burfell tailwater and the head of the Rapids. We do not now believe that the approximately 20 meters of fall between Budafoss and the head of the proposed Urridafoss Reservoir is feasible of power development in the foreseeable future, and do not recommend any studies thereof. We know of no previous investigations and studies for the development of the Skard reach, nor did we inspect it during our field reconnaissance. However, we do believe that it merits some consideration in the overall evaluation of the development of the main stem of the Thjorsa River. Our discussion of possible development is based principally on the small-scale maps and other general information.

Some or all of the 55 meters of head described above may be developed by either one or two dams and associated powerstations. The uppermost dam would be located between the hills, Skardsfjall and Nupsfjall, where the water surface is about 104 meters. An island in the river on this axis might facilitate diversion during construction. The headwater level, on the basis of the 1:50,000 scale maps, might extend to 121 meters, the Burfell Tailwater. The 1:100,000-scale maps, however, show elevations in the vicinity as much as ten meters lower and, if they are more accurate and, in order to develop the full head, a long dike may be required east from Skardsfjall and founded on the permeable Thjorsa lavas. Full development may not be justified and the headwater level may need to be ten meters or more below elevation 121 meters.

The main dam would be about 1.5 kilometers long with a maximum height of about 20 meters if full head development proves feasible. The optimum economic level, however, may require a small sacrifice of head.

The dam would be founded on Thorjsa lavas of adequate strength, but their generally high permeability would require cutoff grouting. A possible route exists for long-path leakage through the Thjorsa lavas to the south of Skardsfjall. The hills at each abutment are probably formed of either Palagonite or Basalt and leakage problems may not be serious. The general geologic setting may be comparable with either Burfell or Tungnaar-krokur, depending on the bedrock composition of the containing hills, and comments previously made with respect to field investigations for those dam and power features would, one or the other, apply generally. The spillway would be a gated concrete structure located in the River channel. The remainder of the dam would probably be of rockfill construction, although concrete types should be considered in whole or in part.

The location and the general types of the power features, and the head to be developed, will require detailed investigations and studies. The comments which follow are based on the assumption of favorable sub-surface conditions. The head to be developed should not be less than to the foot of the rapids at about elevation 85 meters, leaving up to 19 meters to be developed by a second project at Budafoss. The length of water conductors would in that case be about 2.2 kilometers. A surface type of powerhouse would require long steel penstocks with surge tanks because the topography prohibits a headtunnel. A more desirable alternative would be an underground powerstation with the turbines served by individual penstocks connecting directly to the intake, and with a tailtunnel extending to tailwater. This tailtunnel might extend to below Budafoss and thus develop the entire head with a single project. Inadequate cover may require a downstream portion of this water conductor to be in open-cut canal. The relative economics of such a single-stage development must be compared with that of the two-stage development consisting of a project at Skard and a second at Budafoss.

The Budafoss Project as a possible second stage could concentrate up to about 19 meters of head at the falls by that name. Any development to a reservoir level higher than about 80 meters would require long dikes to high ground between the Thjorsa and the Kalfa Rivers, and any additional head between the 80 and 85 meter levels may not, therefore, be justifiable. Moreover, this upper five meters will be about equal to the head loss in the alternative extended tailtunnel from the Skard Project. The entire site would probably be on Thjorsa lavas, and leakage problems may become especially serious as the reservoir level approaches 85 meters.

The Project would include a powerhouse with integral intake, a gated spillway, and any required concrete non-overflow or rockfill wing dams or dikes. The Thjorsa splits its channel just above Budafoss to form the large island, Arnes. A portion of the flow passes over Budafoss while the remainder follows the second channel, Arneskvisl. This natural feature permits the spillway structure to be located on the Arneskvisl with the powerhouse immediately below Budafoss where structural excavation would be a minimum. The spillway would be designed to permit passing nearly all flows without increase in headwater. It would therefore be a low concrete sill surmounted by low gates and piers similar to the arrangement proposed for the Hestvatn Project.

The average discharge of the Thjorsa River at Skard as estimated by the SEA[9] is 365 kl/s. Some regulation by upstream reservoirs should be available by the time the Skard Project (and Budafoss Project) may be constructed. We suggest for present planning purposes that the ultimate station flow capacity be about 520 kl/s. With a single-stage development of the entire 55 meters of gross head the installed capacity would be about 190,000 kilowatts on that flow basis. The average gross annual energy production, assuming adequate regulation to permit nearly full utilization of all flows, would be about 1300 million kilowatt hours.

These capacity and energy values would, on the same general basis, total about the same for the two-stage development, Skard and Budafoss.

Any reasonable appraisal of the Skard Project, whether in one or two stages as discussed above, will require extensive field investigations. These investigations initially would include topographic mapping on a scale of 1:20,000 with five-meter contours of the entire Project area, geologic, reconnaissance and mapping in the vicinity of proposed structures, and some subsurface exploration and testing.

It is our present opinion that the construction of the proposed Skard Project by either proposed alternative would be somewhat more costly on a unit basis than some of the other development possibilities on the Thjorsa-Hvita River System. However, the relatively high flows available are advantageous. We recommend that a general appraisal be made of the Skard Project in the near future.

HAIFOSS PROJECT

The Fossa River is a tributary of the Thjorsa entering one kilometer downstream from the tailwater of the proposed Burfell Project at elevation about 120 meters. The Fossa has a fall of 50 meters in the lower 12.5 kilometers which includes a vertical drop of about twelve meters at the waterfall, Hjalparfoss, four kilometers above its mouth. Power development of this 50-meter drop is not considered feasible, at least in major part. There is a total natural drop of about 308 meters in the seven-kilometer reach immediately upstream. The waterfall, Haifoss, and the Skerholmi Rapids upstream therefrom concentrate a total of 218 meters between elevations 478 and 260 meters in a length of two kilometers at the extreme upper end of this reach. There is thus 90 meters of fall in the other five kilometers downstream.

The Fossa passes through the glacial-eroded basin, Fossolduver, a short distance upstream of the head of the Skerholmi Rapids. A storage volume of 100 million cubic meters below elevation 498 meters may be developed in Fossolduver. An additional 20 million cubic meters of storage might be developed in the Fossardrog Basin located about fourteen kilometers to the northeast near the headwater of the Fossa, but would require diverted inflow from outside the drainage basin which might not be feasible economically.

The high head of 300 meters or more in the Haifoss area appears to present possibilities for construction of a peaking plant whenever capacity may be required in the Southwest Iceland Power Supply System. The associated energy production would be a relatively minor consideration. Peaking operations even at a relatively low plant factor would not require much pondage and the reservoir in Fossolduver could provide some valuable storage useful at downstream plants on the Thjorsa.

The development of the Haifoss Project has been presented by Thoroddsen (1) under the designation "Fossa." His preliminary plans for the storage and diversion dams and for the power features are shown on his Drawings A-1482 and A-1545. The overall Project he proposed includes also the diversion of water from the Dalsa and Kisa Rivers and from the Stora-Laxa and Svarta Rivers into the Fossolduver Basin. The geology of the area including that of the diversion from outside basins has been studied by Kjartansson[2]. The only large-scale topography available is limited to a relatively small area at the damsite on the Fossa proposed by Thoroddsen. Our comments which follow are based principally on the study of the small-scale maps and reports and drawings referred to above, and on other general information. The only part of the area of the Project included in our field reconnaissance was the Fossardalur Valley near the proposed tailtunnel outlets.

The dam on the Fossa would be located a short distance upstream from the head of the Skerholmi Rapids where the water surface is about 478 meters. The site for which topography is available is rather low and flat; a topographically more favorable site may exist a short distance downstream. The dam need only be as high as required to provide pondage for a peaking plant; purchase of head can hardly be justified. For pondage purposes, the dam might be several meters lower than proposed by Thoroddsen. On the other hand, an initial dam constructed for seasonal storage to benefit the overall System may be justified to elevation 500 meters or somewhat higher. This justification could come some years in advance of at-site power development, but after the Urridafoss or other Projects are constructed downstream on the Thjorsa. No additional water supply by diversion from other basins would be required. Therefore, the economics of a storage dam with provisions for adding power features at a later date should be investigated. It is our present opinion that some economy might be achieved compared with the Thoroddsen plan by limiting the concrete structures to a much shorter spillway with an attached intake and greater use of rockfill construction for the dam.

The head would need to be developed by tunnels, with a headtunnel used for the maximum feasible length. The location of the headtunnel, penstocks, underground powerstation, and tailtunnel can only be established after much additional study and investigation of subsurface conditions. The route proposed by Thoroddsen through the mountain, Fossalda, will be through geologically complex formations which include extensive rhyolite intrusions. As stated in Chapter XVII, the rhyolite may give serious trouble in underground excavations and should be avoided unless proven sound by drilling.

On the basis of Kjartansson's general and preliminary map the rhyolite may be avoided by: (1) a route extending farther to the west and downstream which would gain somewhat more head but at greater unit and total costs, or (2) a shorter route which would reenter the Fossa River near the foot of Haifoss, which might sacrifice up to 100 meters of head but probably provide lesser unit and total costs. A route on the east side of the River for the short route is topographically less feasible, and also might encounter rhyolite with depth. As a last resort the water conductors might convey the water to the Thjorsa near the mouth of the Tungnaa but they would be about seven kilometers long and the gross head would be only about 210 meters. The comparable length for the long Fossalda route referred to above would be about six kilometers, and for the short route about 2.5 kilometers. Detailed studies are required to establish a feasible route for the water conductors and to determine the optimum amount of head to be developed. The short route to near the foot of Haifoss, developing about 240 meters of gross head, appears at this time as probably the most feasible technically and may have the lowest unit costs.

A continuous automatic stage recorder was installed on the Fossa River near Haifoss in November 1958. Correlation studies made for that station by the SEA[(1)] estimate an average discharge of 7.5 kl/s with the monthly averages ranging between four and fifteen kl/s. The drainage area is listed as 125 square kilometers, but our map measurements indicate that much area above the proposed damsite, with about 20 square kilometers intervening between the damsite and the gage. We have assumed the natural average inflow into the Fossolduver Reservoir to be 6.5 kl/s, to be conservative. The average annual yield would then be about 200 million cubic meters or about twice the storage potential in Fossolduver to elevation 498 meters.

Thoroddsen proposed the diversion of the Dalsa River to the Fossa drainage with a dam located just downstream of its confluence with the Oraefakvisl tributary and a tunnel about eleven kilometers long leading to the Fossardrog Basin near the headwaters of the Fossa. This Basin could be the site of a small storage and reregulating reservoir. The flow therefrom would be by gravity to Fossolduver, about 80 meters lower. The drainage area at the Dalsa damsite is about 243 square kilometers. We know of no discharge records or correlation studies for the River. The estimated average flow would be about 12.5 kl/s on the basis of drainage area proportion with the Fossa. No appreciable storage appears feasible behind the dam; therefore the tunnel would need to be sized to pass flows higher than average, probably up to about 30 kl/s. This rate would call for a rather small-diameter tunnel, four meters or less, and the unit cost of excavation would be high.

It is our opinion that the Dalsa Diversion cannot be justified economically. The Dalsa water can be utilized for power and energy through about 300 meters of gross head at the proposed Dynkur and Burfell Projects in the Thjorsa River. The flow reduction to those plants resulting from diversion to the Fossa would be unfavorable economically to them. We do not consider any further studies justified at this time with respect to the proposed diversion of the Dalsa River.

Thoroddsen also suggested the diversion of waters from the Stora-Laxa River to the Fossolduver Reservoir with a dam in that stream east of the mountain, Geldingafell, and a five-kilometer long tunnel. The waters of the Svarta River, a tributary of the Stora-Laxa, would be added to the tunnel as it passes thereunder. The total area tributary to the two diversions is about 140 square kilometers. Again, we know of no discharge records or flow correlation studies. The average flow to be diverted estimated on the basis of drainage area proportion to the Fossa would be about seven kl/s. No appreciable storage is feasible above the diversion structure on either stream and the diversion capacity for the tunnel may need to be about 20 kl/s or somewhat greater. Thoroddsen proposed a tunnel of about eight square meters cross-section which should be very ample. This would also be a relatively small-size high unit cost tunnel. This additional inflow into Fossolduver would have only a minor bearing on storage therein and would not be required for that purpose.

No power developments have, to our knowledge, been proposed on the Stora-Laxa downstream of the diversion, nor have we made studies for any specific developments thereon. On the basis of map reconnaissance, the stream does not appear favorable for development of either low-cost power or storage. There are no moderately high concentrations of head or open basins. Development thereon is improbable for many years. The flow diverted to the Fossa would be lost for power only at the proposed Hestvatn and Selfoss Projects, where the total head is only about 24 meters. However, the economics of the diversion are somewhat questionable and more detailed investigations and studies are required to permit a definite determination in that regard. No detailed topography is now available at the sites of the proposed structures. The possible fault zones along the tunnel route require special study and investigations. Zones of weaknesses of that general type sometimes contain material erodable under high hydrostatic pressure and have been the cause of serious tunnel-driving problems elsewhere on numerous recent occasions.

It is our opinion that the power features of the Haifoss Project should be designed, on an ultimate basis, for a plant capacity factor on the order of 25 percent. The plant flow capacity on that basis would be about 25 kl/s without consideration of any diverted inflow. The installed capacity would be about 50,000 kilowatts with tailwater at the foot of Haifoss, and about 70,000 kilowatts with the long tunnel route. The average annual energy production is of much less importance than capacity but would amount to about 110 million and 150 million kilowatthours for the short and long tunnel routes, respectively. The diversion from the Stora-Laxa and Svarta would about double each of these estimates.

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LIST OF EXHIBITS

ESTIMATED ENGINEERING COSTS IN U.S. DOLLARS

Project or River Reach	Reference Chapter	Estimated Cost of Work by Type: Topography	Geologic Studies	Hydrographic Surveys	Foundation Investigations	Materials Investigations	Office Studies	Total
HVITA RIVER								
Hestvatn	V	5,000	500	4,000	16,000	2,500	12,000	40,000
Hvitarvatn Storage	VI	5,000	500	500	20,000	3,000	13,000	42,000
Blafell	VII	2,000	2,000	1,000	10,000	1,000	25,000	41,000
Gullfoss	VIII	15,000	5,000	1,000	40,000	3,000	20,000	84,000
Apavatn & Dynjandi	XVIII	5,000	1,000	4,000	6,000	1,000	5,000	22,000
Vordufell Pumped Storage	XVIII	-	1,000	-	-	-	4,000	5,000
Vatnsleysufoss	XVIII	8,000	2,000	1,000	8,000	2,000	10,000	31,000
Selfoss	XVIII	-	1,000	2,000	10,000	2,000	10,000	25,000
Subtotals Hvita		40,000	13,000	13,500	110,000	14,500	99,000	290,000
THJORSA RIVER								
Urridafoss	X	7,500	2,000	4,000	28,000	3,500	15,000	60,000
Thorisvatn Storage and Kaldakvisl Diversion	XI	1,000	2,000	1,000	30,000	5,000	20,000	59,000
Upper Thjorsa	XII	15,000	5,000	1,000	30,000	4,000	20,000	75,000
Tungnaarkrokur	XIII	-	5,000	1,000	80,000	5,000	15,000	106,000
Hrauneyjafoss	XIV	1,000	5,000	1,000	70,000	2,000	20,000	99,000
Lower Tungnaa	XV	2,000	2,000	1,000	15,000	2,000	8,000	30,000
Upper Tungnaa	XVI	2,000	3,000	1,000	24,000	3,000	15,000	48,000
Burfell and Sultartangi	XVII	10,000	4,000	1,000	48,000	5,000	25,000	93,000
Skard	XVIII	10,000	2,000	1,000	15,000	3,000	10,000	41,000
Haifoss	XVIII	4,000	3,000	1,000	10,000	2,000	10,000	30,000
Subtotals Thjorsa		52,500	33,000	13,000	350,000	34,500	158,000	641,000
System Operation Studies								50,000
TOTALS		92,500	46,000	26,500	460,000	49,000	257,000	981,000

Note: Estimates based on appraisal studies for developing Master Plan.

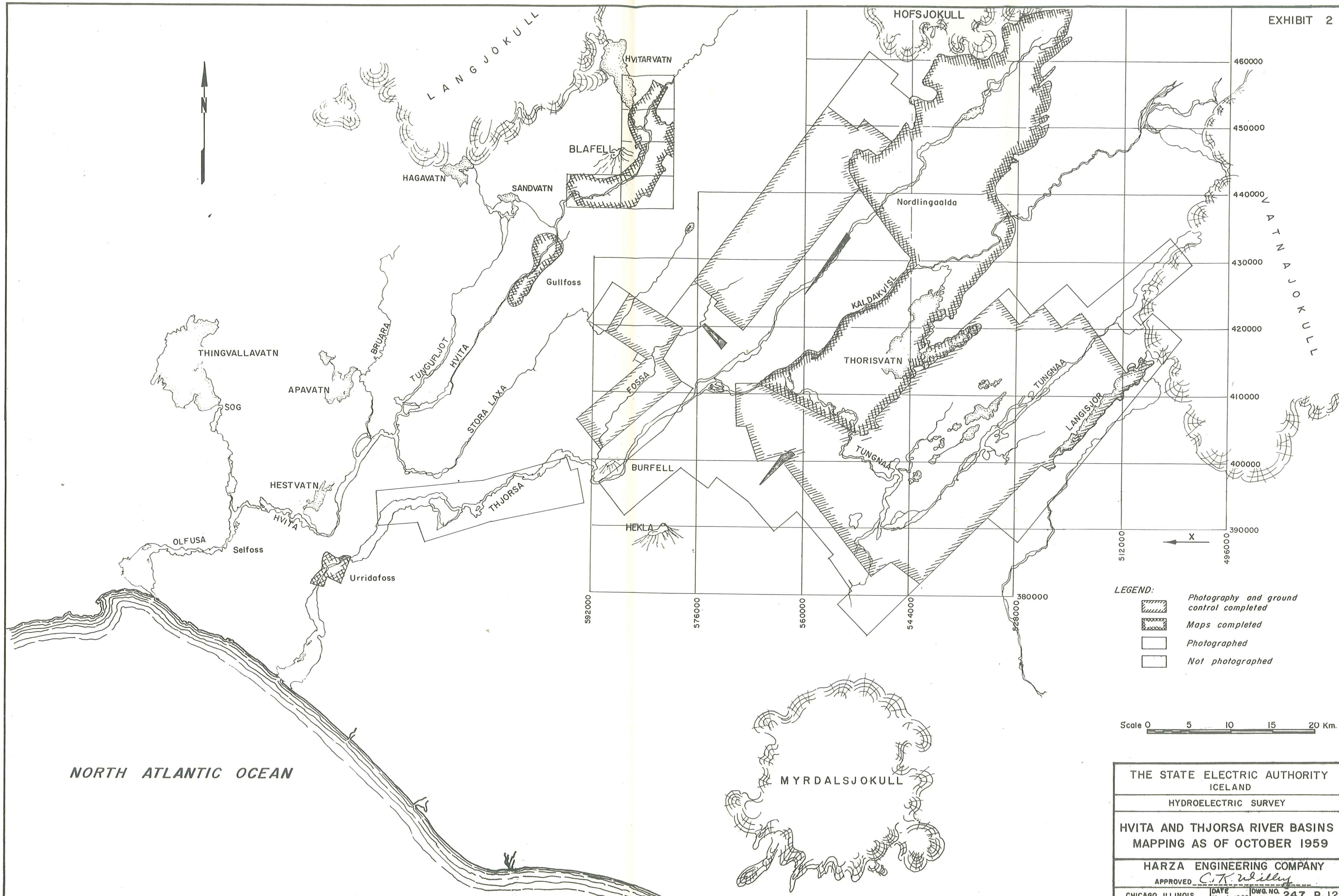


EXHIBIT 2
HOFSJOKULL
LANGJOKULL
HVITARVATN
BLAFELL
HAGAVATN
SANDVATN
Nordlingaalda
VATNAJOKULL
Gullfoss
KALDAKVISL
THINGVALLAVATN
BRUARA
TUNGUFLJOT
HVITA
APAVATN
THORISVATN
TUNGNAA
FOSSA
STORA LAXA
SOG
LANGISJOR
TUNGNAA
BURFELL
HESTVATN
THJORSA
HVITA
HEKLA
OLFUSA
Selfoss
Urridafoss
460000
450000
440000
430000
420000
410000
400000
390000
380000
592000
576000
560000
544000
528000
512000
496000
X
LEGEND:
Photography and ground control completed
Maps completed
Photographed
Not photographed
Scale 0 5 10 15 20 Km.
NORTH ATLANTIC OCEAN
MYRDALSJOKULL
THE STATE ELECTRIC AUTHORITY
ICELAND
HYDROELECTRIC SURVEY
HVITA AND THJORSA RIVER BASINS
MAPPING AS OF OCTOBER 1959
HARZA ENGINEERING COMPANY
APPROVED C. K. Willey
CHICAGO, ILLINOIS
DATE March, 1960
DWG. NO. 247 P 12

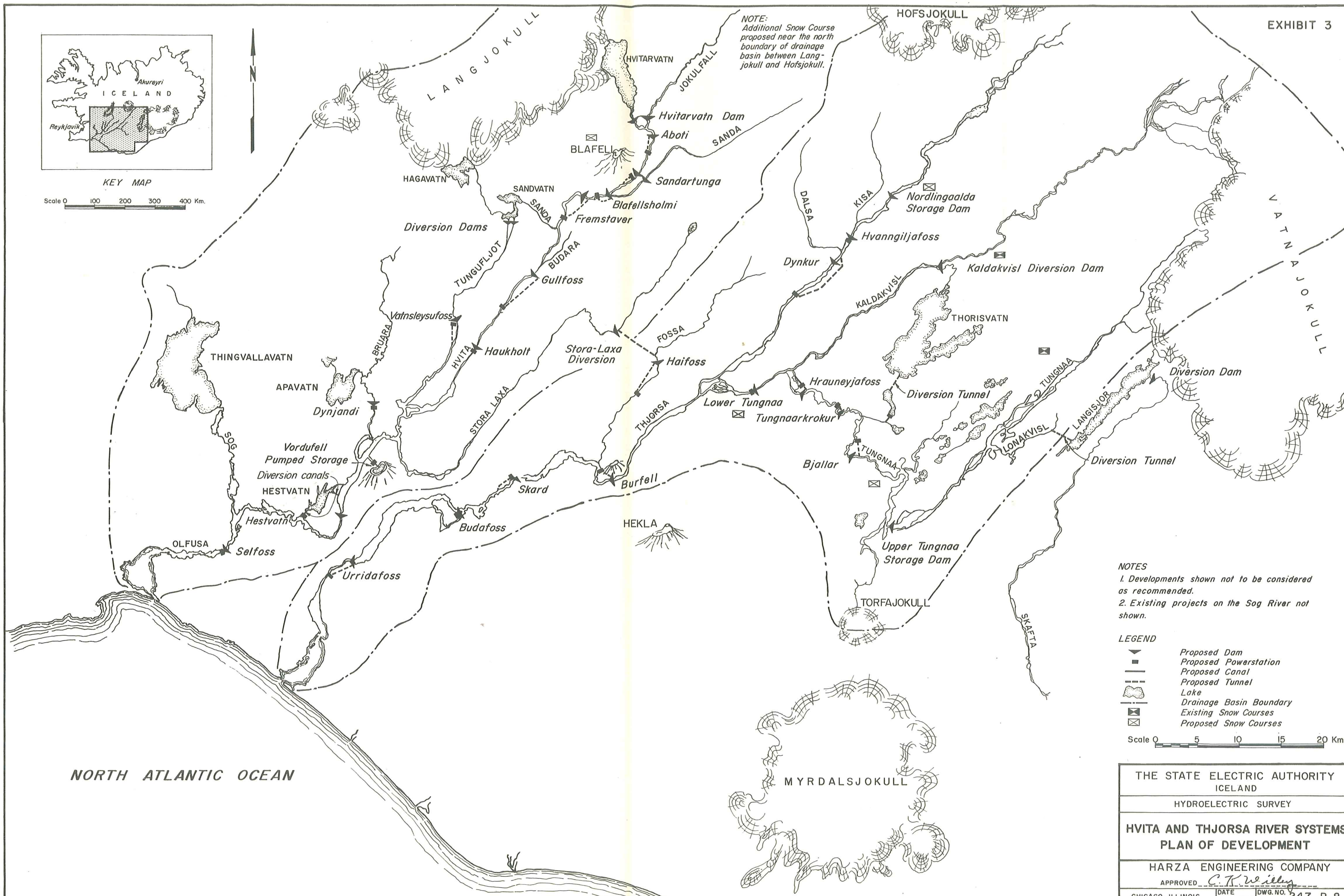
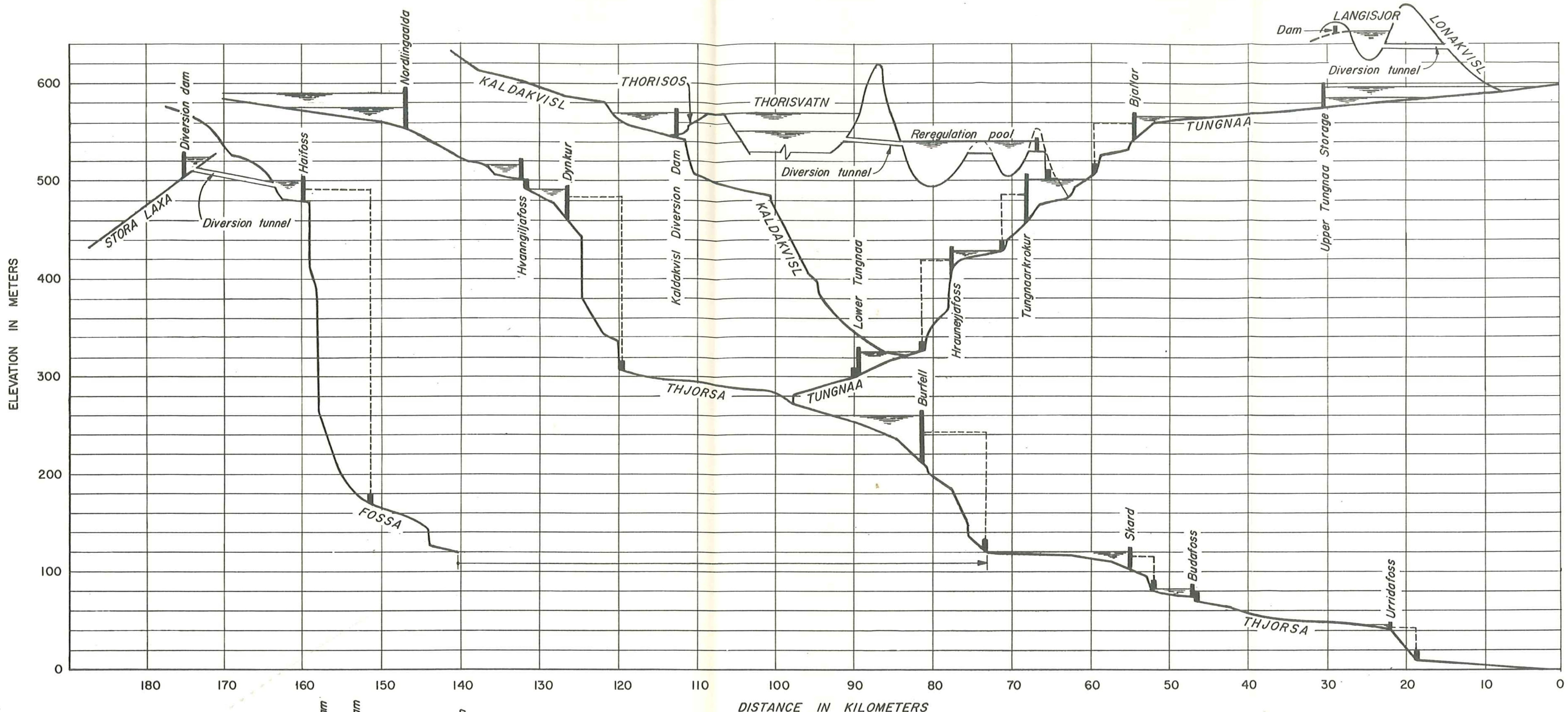


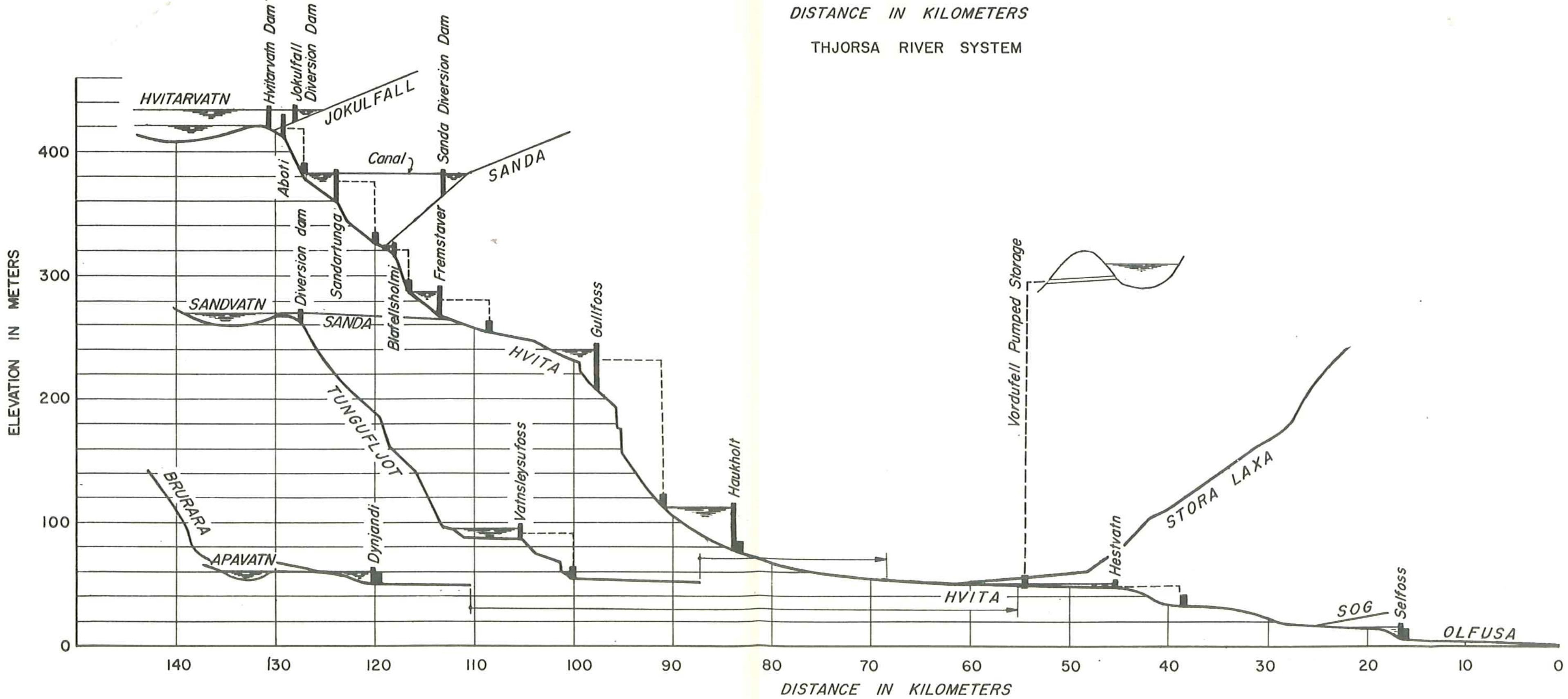
EXHIBIT 3
NOTE:
Additional Snow Course proposed near the north boundary of drainage basin between Langjokull and Hofsjokull.
KEY MAP
ICELAND
Akureyri
Reykjavik
Scale 0 100 200 300 400 Km.
N
LANGJOKULL
HOFSJOKULL
VATNAJOKULL
HVITARVATN
JOKULFALL
Hvitarvatn Dam
Aboti
SANDA
BLAFELL
Sandartunga
HAGAVATN
SANDVATN
SANDA
Blafellsholmi
Fremstaver
Diversion Dams
TUNGUFLJOT
BUDARA
Gullfoss
DALSA
KISA
Nordlingaalda Storage Dam
Hvanngiljafoss
Dynkur
Kaldakvisl Diversion Dam
KALDAKVISL
THORISVATN
FOSSA
Haifoss
Stora-Laxa Diversion
Vatnsleysufoss
BRUARA
HVITA
Haukholt
THINGVALLAVATN
APAVATN
Dynjandi
STORA LAXA
THJORSA
Lower Tungnaa
Tungnaarkrokur
Hrauneyjafoss
Diversion Tunnel
TUNGNAA
LANGISJOR
Diversion Dam
LONAKVISL
Diversion Tunnel
Bjallar
TUNGNAA
SOG
Vordufell Pumped Storage
Diversion canals
HESTVATN
Hestvatn
Skard
Burfell
Budafoss
HEKLA
OLFUSA
Selfoss
Urridafoss
Upper Tungnaa Storage Dam
TORFAJOKULL
SKAFTA
NOTES
1. Developments shown not to be considered as recommended.
2. Existing projects on the Sog River not shown.
LEGEND
Proposed Dam
Proposed Powerstation
Proposed Canal
Proposed Tunnel
Lake
Drainage Basin Boundary
Existing Snow Courses
Proposed Snow Courses
Scale 0 5 10 15 20 Km.
NORTH ATLANTIC OCEAN
MYRDALSJOKULL
THE STATE ELECTRIC AUTHORITY
ICELAND
HYDROELECTRIC SURVEY
HVITA AND THJORSA RIVER SYSTEMS
PLAN OF DEVELOPMENT
HARZA ENGINEERING COMPANY
APPROVED C. K. Willey
CHICAGO, ILLINOIS
DATE March, 1960
DWG. NO. 247 P 8

EXHIBIT 4



THJORSA RIVER SYSTEM

NOTES
1. *Developments shown not to be considered as recommended.*
2. *Diversion schemes shown are for illustrative purposes only and are not to scale.*
3. *Basic profiles plotted from SEA river survey.*



HVITA RIVER SYSTEM

DATE	NO	DISTRIBUTION

PRINTS

	BY	DATE	CHKD.	DATE
DSGN.				
DWN.	WET	3/1/60	ARE	3/18/60
DEPT.	SQUAD LEADER	SECT. HEAD	DEPT. HEAD	
CIVIL	ARE			
MECH.				
ELECT.				
PLAN.				
STAFF			CH.ENGR.	

REV. NO.	DATE	NATURE OF REVISION	BY	CHKD.	APPD.

THE STATE ELECTRICITY AUTHORITY
ICELAND

HYDROELECTRIC SURVEY

HVITA AND THJORSA RIVER SYSTEMS PROFILES OF DEVELOPMENT

HARZA ENGINEERING COMPANY
APPROVED C. K. Willey

CHICAGO, ILLINOIS | DATE MARCH 1960 | DWG. NO. 247 P II

PROJECT	HEADWATER ELEVATION Meters	TAILWATER ELEVATION Meters	GROSS HEAD Meters	LENGTH OF WATER CONDUCTOR Kilometers	STORAGE VOLUME Million M^3	RESERVOIR DRAWDOWN Meters	NET HEAD - Meters		AVERAGE FLOW Kl/s	STATION FLOW CAPACITY (3) Kiloliters per Second		STATION OUTPUT CAPACITY (4) Kilowatts		GROSS AVERAGE ANNUAL ENERGY (5) Million Kwh
							@ STATION FLOW CAPACITY (1)	@ AVERAGE FLOW (2)		BASE LOAD PLANT	PEAKING PLANT	BASE LOAD PLANT	PEAKING PLANT	
HVITA RIVER BASIN														
HVITA RIVER														
Hvitarvatn Storage	435	—	—	—	800	14	—	—	77 (6)					
Blafell														
Aboti II	420	385	35	2.0	—	—	32.0	33.0	77	110	—	30,000	—	180
Sandartunga IIIA	385	325	60	3.5	—	—	55.0	56.5	102	145	—	65,000	—	400
Blafellsholmi	325	287	38	1.0	—	—	36.5	37.0	102	145	—	45,000	—	260
Fremstaver	287	252	35	4.0	—	—	32.0	33.0	102	145	—	40,000	—	240
Gullfoss	242	114	128	7.0	—	—	117.5	121.0	140 (7)	—	280	—	270,000	1120 (12)
Haukholt	114	77	37	–	—	—	37.0	37.0	145 (7)	210	—	65,000	—	370
Hestvatn	50	33	17	2.0	—	—	15.5	16.0	262	375	—	50,000	—	290
Selfoss	14	7	7	–	—	—	7.0	7.0	386	550	—	30,000	—	190
BRUARA RIVER														
Apavatn Storage	60	—	—	—	50	5	—	—	—					
Dynjandi	60	50	10				9.0	9.0	66	100	—	7,000	—	40
TUNGUFLJOT RIVER														
Vatnsleysufoss	96	56	40	5.0	—	—	32.5	35.0	25 (8)	35	—	9,000	—	60
THJORSA RIVER BASIN														
THJORSA RIVER														
Nordlingaalda Storage	590	—	—	—	1200	15	—	—	99					
Hvanngiljafoss	515	490	25	—	—	–	25.0	25.0	110	160	—	35,000	—	190
Dynkur	490	305	185	8.0	—	—	173.0	177.0	125	—	250	—	360,000	1600
Burfell	260	121	139	2.5	1000	20	130.0	131.5	334	—	670	—	710,000	3100
Skard	121	85	36	2.0	—	—	33.0	34.0	365	520	—	140,000	—	870
Budafoss	80	66	14	-	—	—	14.0	14.0	365	520	—	60,000	—	360
Urridafoss	46	11	35	2.5	—	—	31.0	32.5	377	540	—	140,000	—	850
KALDAKVISL RIVER														
Thorisvatn Storage	571	—	—	—	1500	27	—	—	45 – 50					
TUNGNAA RIVER														
Langisjor Storage	660	—	—	—	500	20	—	—	15					
Bjallar	565	505	60	3.0	200	15	51.5	53.0	95 (9)	135	—	55,000	—	350
Tungnaarkrokur	500	425	75	1.5	200	20	68.0	68.5	160 (10)	230	—	130,000	—	770
Hrauneyjafoss	425	325	100	3.0	—	—	95.5	97.0	169 (10)	240	—	190,000	—	1100
Lower Tungnaa	325	300	25	—	—	—	25.0	25.0	202 (10)	290	—	60,000	—	350
FOSSA RIVER														
Haifoss	500	260	240	2.5	100	12	233.0	234.5	6.5 (11)	—	25	—	70,000	110
SUB-TOTAL HVITA RIVER BASIN					850							341,000	270,000	3150
SUB-TOTAL THJORSA RIVER BASIN					4700							810,000	1,140,000	9650
TOTAL ALL DEVELOPMENTS					5550							2,561,000		12,800

REFERENCE NOTES

1. Represents gross head reduced by 25% of reservoir drawdown plus friction losses in water conductors amounting to 1.5 m/km for tunnels and 0.75 m/km for canals.
2. Same as (1) except friction losses amount to 1.0 and 0.5 m/km for tunnels and canals, respectively.
3. Base load and peaking based on 70% and 50% capacity factors, respectively; referred to average flow; except at Haifoss where 25% capacity factor is assumed.
4. Station capacity computed from formula: $Kw = 8.2\,Q_s\,H_n$ where
   Q_s = Station flow capacity and
   H_n = Net head at station capacity
5. Annual energy computed from formula: $Kwh = 8.4\,(8760)\,Q_a\,H_a$ where
   Q_a = Average flow x water utilization factor, 0.95 and
   H_a = Net head at average flow
6. Includes 25 kiloliters per second from Jokulfall Diversion.
7. Includes 22 kiloliters per second from Sandvatn Diversion.
8. Reduced by 22 kiloliters per second diverted to Hvita at Sandvatn.
9. Includes 15 kiloliters per second from Langisjor Diversion.
10. Includes 47 kiloliters per second from Thorisvatn and 15 kiloliters per second from Langisjor Diversion.
11. Does not include diversion from other watersheds.
12. Reduced 6% to allow for water released to falls.

GENERAL NOTE

Data tabulated above is preliminary only and should not be considered as our recommended development for each project.

DATE	NO	DISTRIBUTION	
PRINTS			
	BY	DATE	CHKD. DATE
DSGN.			
DWN.	Jason	3/7/60	ARE 3/15/60
DEPT.	SQUAD LEADER	SECT. HEAD	DEPT. HEAD
CIVIL	ARE		
MECH.			
ELECT.			
PLAN.			
STAFF			CH. ENGR.

REV. NO.	DATE	NATURE OF REVISION	BY	CHKD.	APPD.

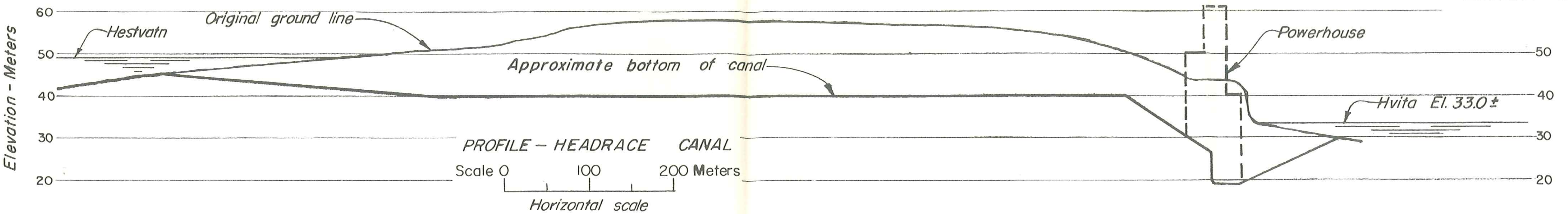
THE STATE ELECTRICITY AUTHORITY
ICELAND

HYDROELECTRIC SURVEY

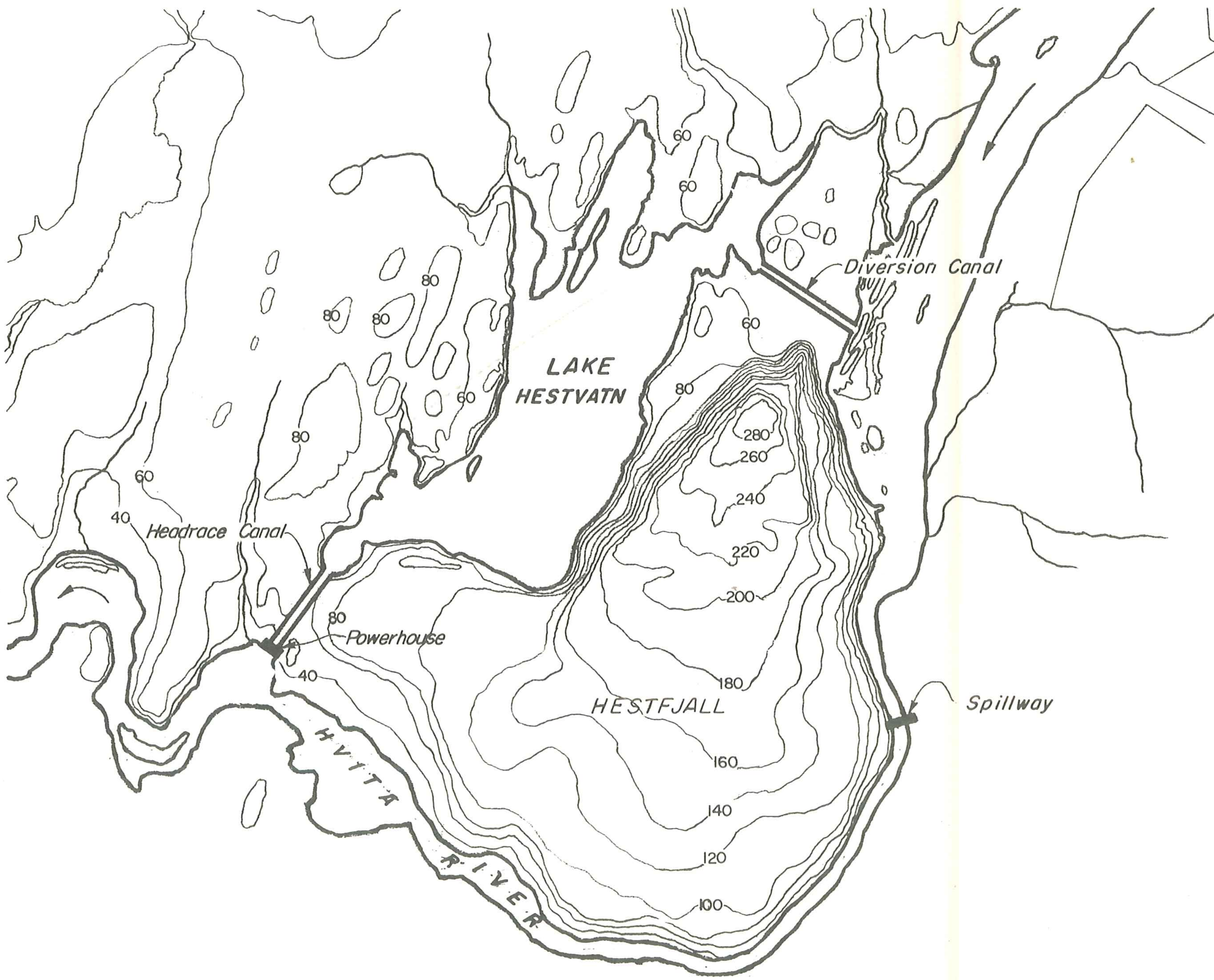
HVITA AND THJORSA RIVER SYSTEMS PROJECT DATA

HARZA ENGINEERING COMPANY
APPROVED C. K. Willey
CHICAGO, ILLINOIS | DATE MARCH, 1960 | DWG. NO. 247 P 13

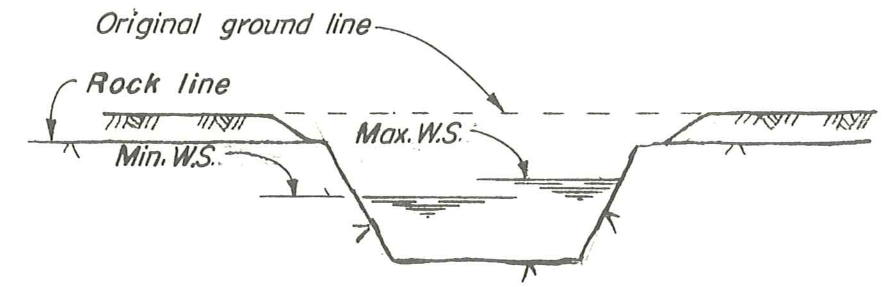
EXHIBIT 6



PROFILE – HEADRACE CANAL



GENERAL PLAN



TYPICAL HEADRACE CANAL SECTION
Not to scale

NOTE:
Topography based on 1:50,000 U.S. Army Maps with 20 meter contour interval.

Contour interval 20m.

Scale 0 1000 2000 Meters
1:50,000
Except as noted

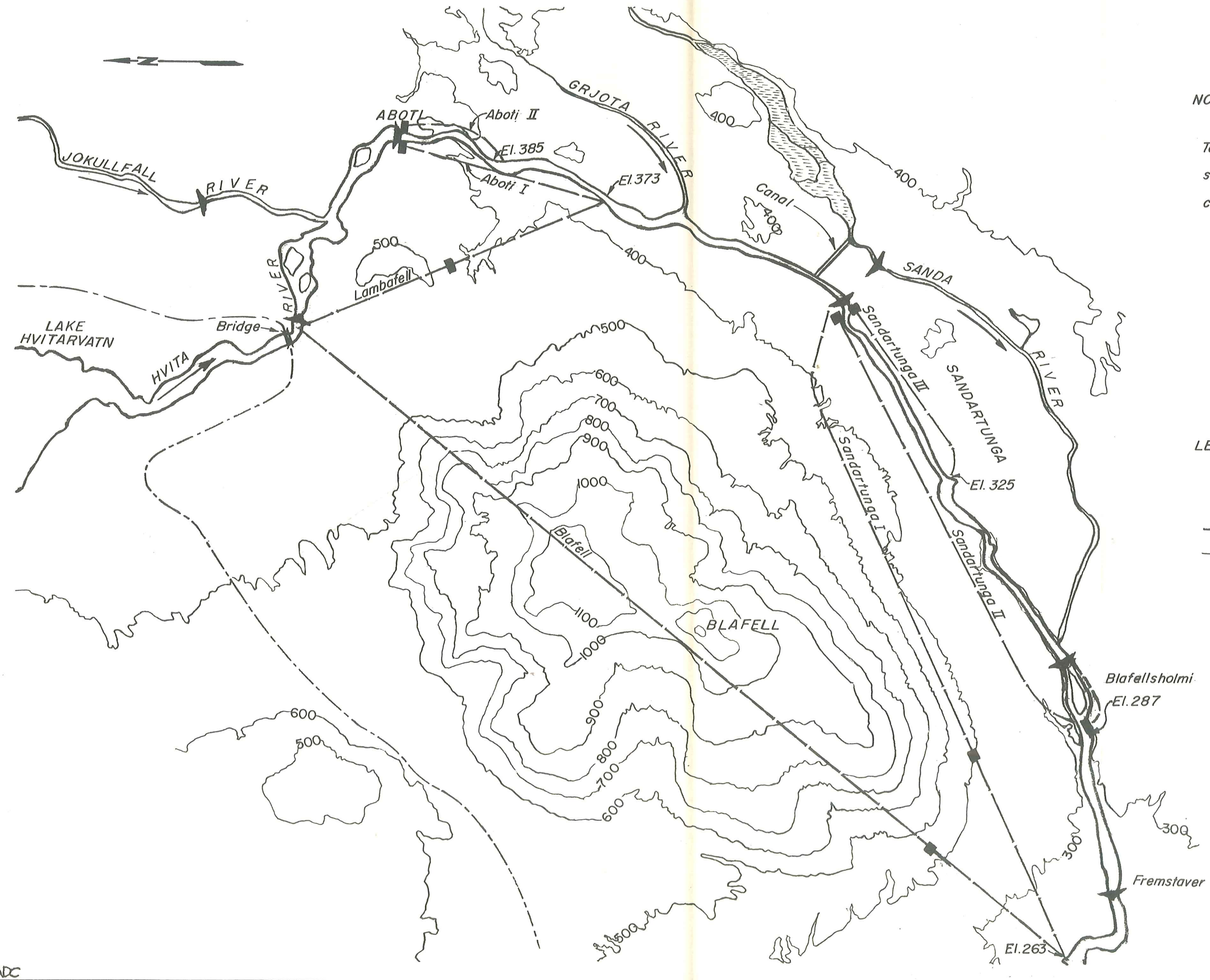
THE STATE ELECTRICITY AUTHORITY
ICELAND

HESTVATN PROJECT

HARZA ENGINEERING CO., CHICAGO
APPROVED C. K. Willey

DATE March, 1960 | DWG. NO. 247 P 6

EXHIBIT 7



NOTES:

Topography based on Army Maps in scale 1:50,000 and with 20 meter contour intervals

LEGEND:

Dam

Power station

Tunnel

Existing road

Contour interval: 100 m.

Scale 0 1000 2000 Meters

1:50,000

THE STATE ELECTRICITY AUTHORITY
ICELAND

BLAFELL
DEVELOPMENT

HARZA ENGINEERING CO., CHICAGO
APPROVED C. K. Willey

DATE March, 1960 DWG. NO. 247P14

K+E ALBANENE 195L TRACING PAPER

EXHIBIT 8

NOTE:
Topography reduced from 1:5,000 SEA ground survey maps.

Contour interval 2.5 m

Scale 0 400 800 Meters
1:20,000

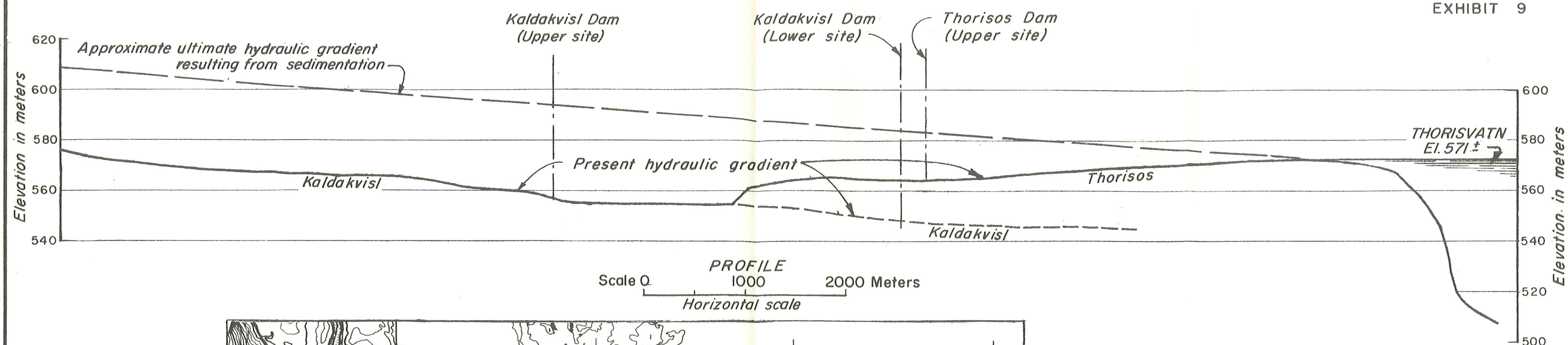
THE STATE ELECTRICITY AUTHORITY
ICELAND

URRIDAFOSS
PROJECT

HARZA ENGINEERING CO. CHICAGO
APPROVED C. K. Willey

DATE March, 1960 | DWG. NO. 247 P 5

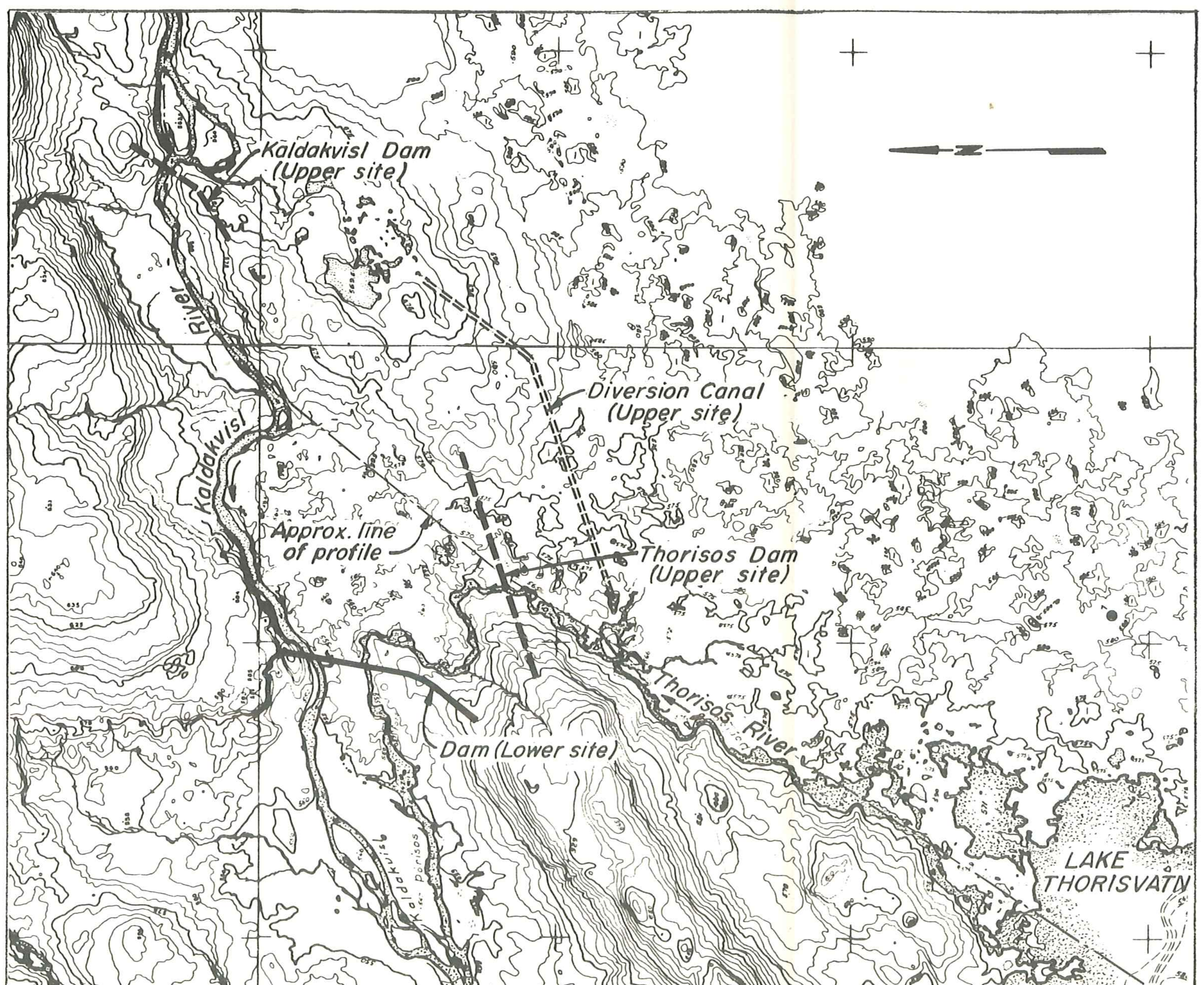
EXHIBIT 9



PROFILE

Scale 0 1000 2000 Meters

Horizontal scale



NOTE:

Topography reduced from SEA 1:20,000 aerial survey maps.

Contour interval 5m

Scale 0 500 1000 1500 Meters

1:40,000

THE STATE ELECTRICITY AUTHORITY
ICELAND

KALDAKVISL - THORISVATN
DIVERSION

HARZA ENGINEERING CO., CHICAGO

APPROVED C. K. [signature]

DATE March, 1960

DWG. NO. 247 P 7

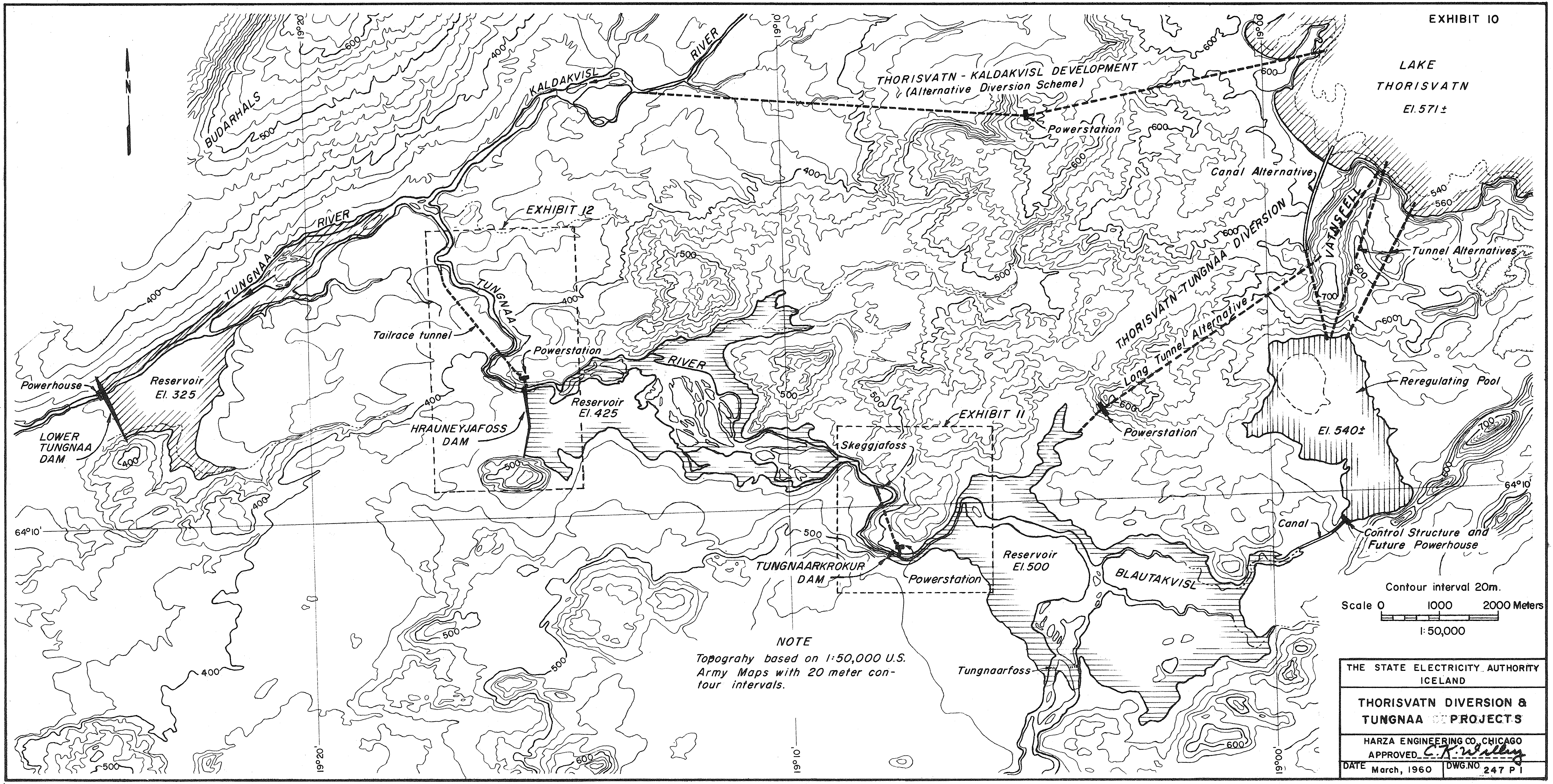
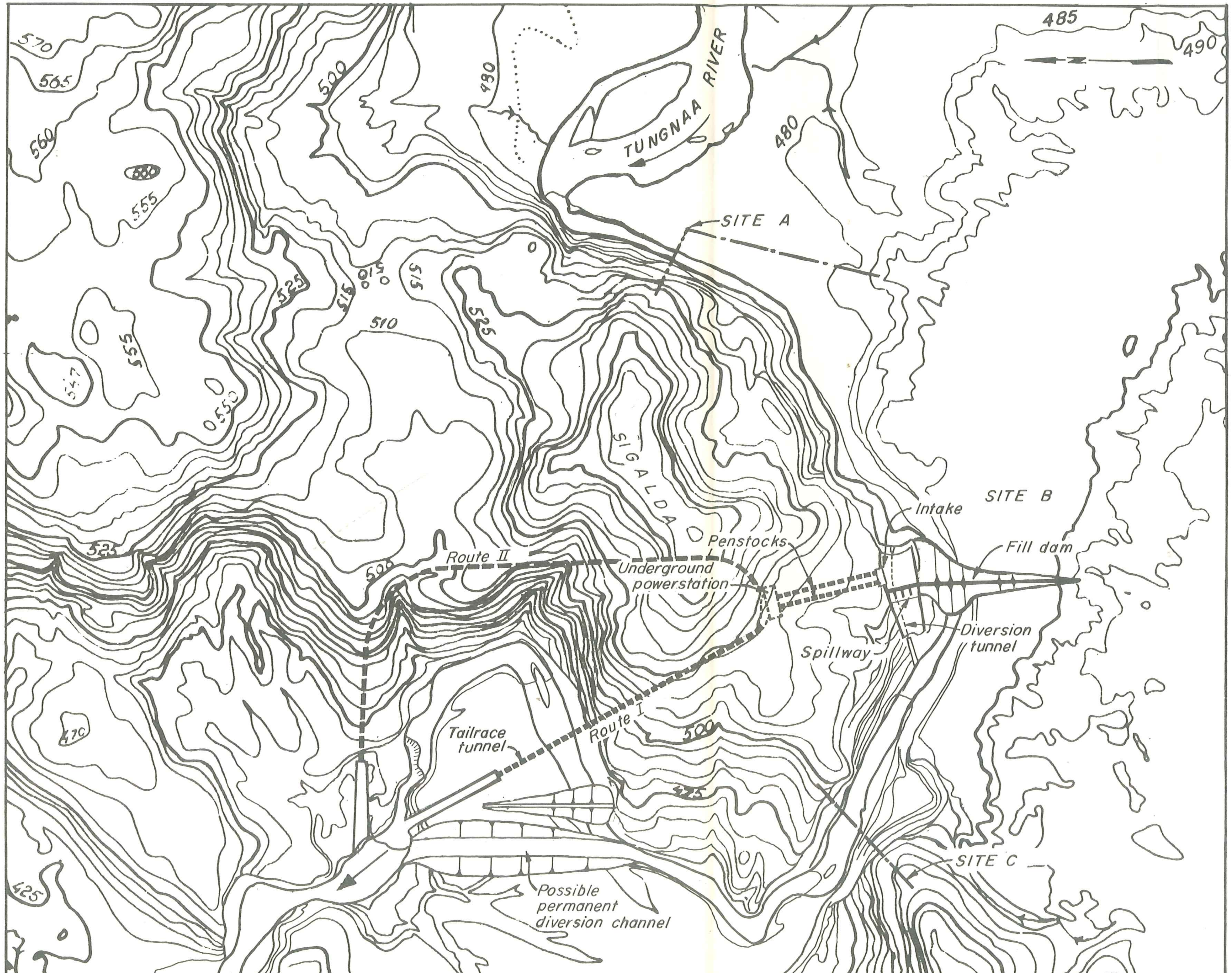


EXHIBIT 10
N
LAKE THORISVATN
El. 571±
THORISVATN - KALDAKVISL DEVELOPMENT
(Alternative Diversion Scheme)
Powerstation
KALDAKVISL
RIVER
BUDARHALS
Canal Alternative
VATNSFELL
Tunnel Alternatives
THORISVATN-TUNGNAA DIVERSION
Long Tunnel Alternative
Powerstation
Reregulating Pool
El. 540±
EXHIBIT 12
TUNGNAA
RIVER
TUNGNAA
Tailrace tunnel
Powerstation
Powerhouse
Reservoir
El. 325
LOWER
TUNGNAA
DAM
Reservoir
El. 425
RIVER
HRAUNEYJAFOSS
DAM
EXHIBIT 11
Skeggjafoss
TUNGNAARKROKUR
DAM
Powerstation
Reservoir
El. 500
BLAUTAKVISL
Canal
Control Structure and
Future Powerhouse
Tungnaarfoss
64°10'
19°20
19°10
19°00
Contour interval 20m.
Scale 0 1000 2000 Meters
1:50,000
NOTE
Topograhy based on 1:50,000 U.S.
Army Maps with 20 meter con-
tour intervals.
THE STATE ELECTRICITY AUTHORITY
ICELAND
THORISVATN DIVERSION &
TUNGNAA PROJECTS
HARZA ENGINEERING CO. CHICAGO
APPROVED C.K. Willey
DATE March, 1960
DWG.NO 247 P1

EXHIBIT II



NOTES:

Development shown not to be considered as recommended.

Topography enlarged from 1: 20,000 SEA aerial survey map.

Contour interval 5m

Scale 0 200 400 Meters

1:10,000

THE STATE ELECTRICITY AUTHORITY ICELAND	
TUNGNAARKROKUR PROJECT	
HARZA ENGINEERING CO., CHICAGO APPROVED C. K. Willey	
DATE March, 1960	DWG. NO. 247 P 2

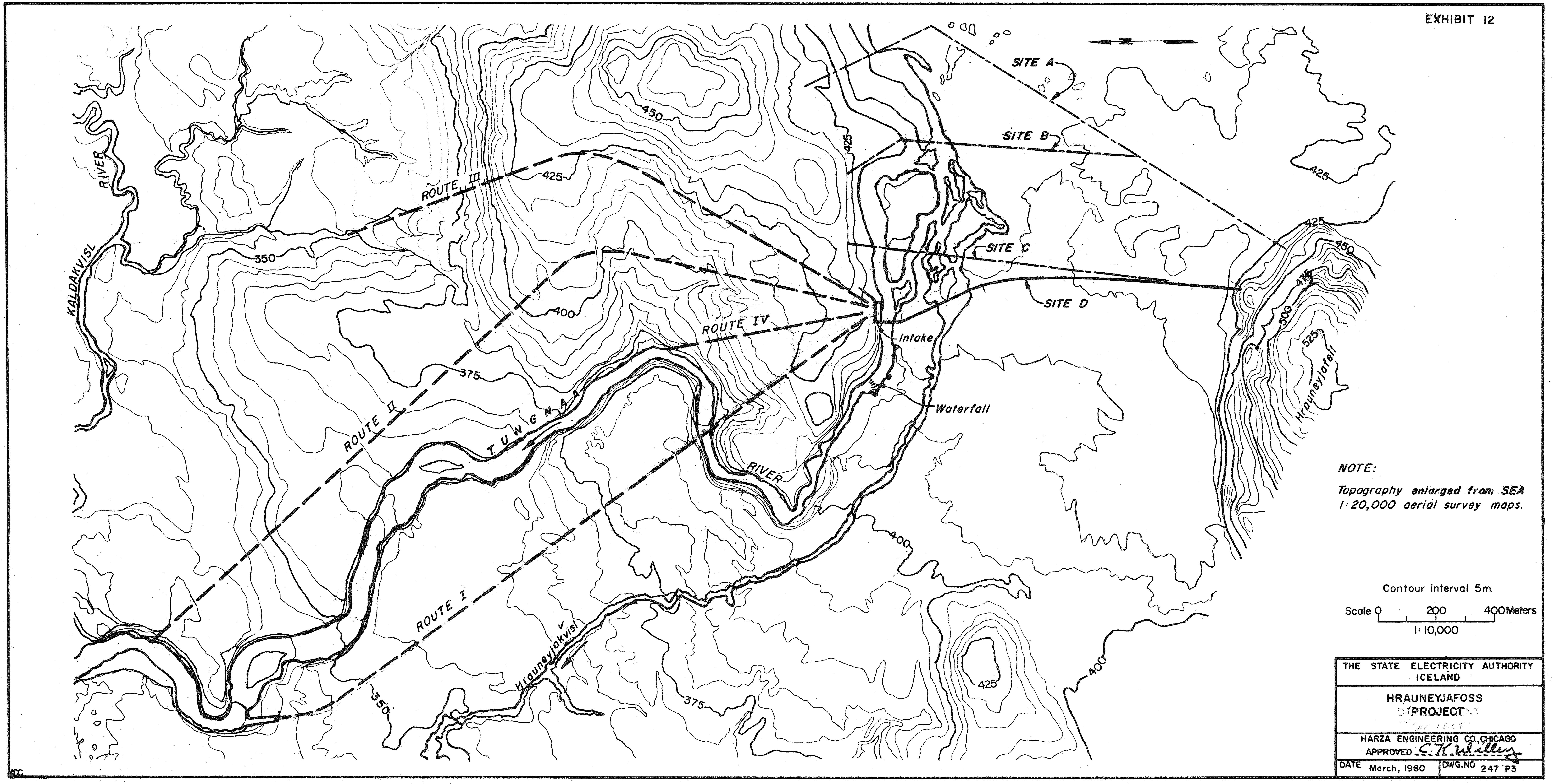
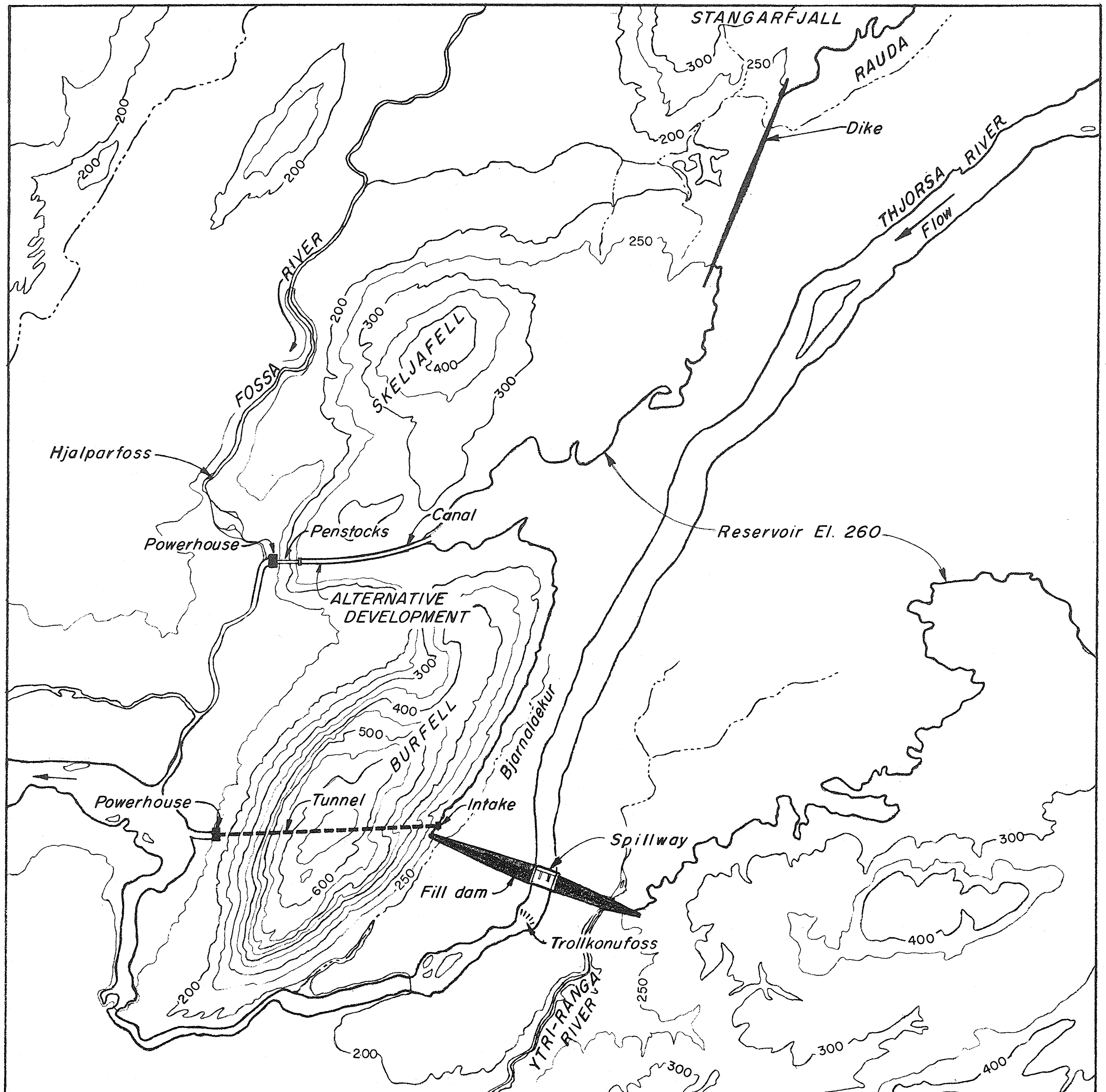


EXHIBIT 12
N
SITE A
SITE B
SITE C
SITE D
ROUTE I
ROUTE II
ROUTE III
ROUTE IV
Intake
Waterfall
TUNGNAA
RIVER
KALDAKVISL
RIVER
Hrauneyjakvisl
Hrauneyjafell
350
375
400
425
450
475
500
525
NOTE:
Topography enlarged from SEA 1:20,000 aerial survey maps.
Contour interval 5m.
Scale 0 200 400 Meters
1:10,000
THE STATE ELECTRICITY AUTHORITY ICELAND
HRAUNEYJAFOSS PROJECT
HARZA ENGINEERING CO, CHICAGO
APPROVED
DATE March, 1960
DWG. NO 247 P3

EXHIBIT 13



N

NOTES:

Developments shown not to be considered as recommended.

Topography based on 1:50000 U.S. Army Maps with 20-meter contour intervals.

Contour interval 50m.

Scale 0 1000 2000 Meters

1:50,000

THE STATE ELECTRICITY AUTHORITY ICELAND	
BURFELL PROJECT	
HARZA ENGINEERING CO., CHICAGO APPROVED C. K. Willey	
DATE March, 1960	DWG. NO. 247 P 4