

GOVERNMENT AND INDUSTRY INTERACTIONS
IN THE DEVELOPMENT OF CLOCK TECHNOLOGY

Helmut Hellwig
Frequency and Time Systems, Inc.

ABSTRACT

It appears likely that everyone in the time and frequency community can agree on goals to be realized through the expenditure of resources. These goals are the same as found in most fields of technology: lower cost, better performance, increased reliability, small size and lower power. This paper focuses on related aspects in the process of clock and frequency standard development which sees government and industry in a highly interactive role. These interactions include judgments on clock performance, what kind of clock, expenditure of resources, transfer of ideas or hardware concepts from government to industry, and control of production. The author believes that successful clock development and production requires a government/industry relationship which is characterized by long-term continuity, multi-disciplinary team work, focused funding and a separation of reliability and production oriented tasks from performance improvement/research-type efforts.

THE CLOCK HIERARCHY

Figure 1 shows the existing clock hierarchy, a commonly accepted ranking of clock types.¹ This ranking is not only based on the physical characteristics but also on the technology used; i.e., the crystal resonator, the rubidium gas cell, the cesium beam tube and the hydrogen storage bulb maser. We must remember that any of these concepts or atoms can be used in different combinations as we will discuss later.

This ranking of today's principal precision clocks and frequency standards is meaningful as shown in Figure 1. Listed is the typical best stability or flicker of frequency floor, σ_F , as well as the typical Q values. Figure 1 shows that increasing Q's ranging from 2 million with a crystal resonator to 1 billion with the hydrogen

storage bulb, correlate¹ to frequency stability improvements from 1×10^{-12} to 3×10^{-15} . However, we also note that size and cost correspondingly increase. Thus, we conclude that the ranking of today's frequency standards may not necessarily be based on a fundamental difference governing the crystal resonator vs. the rubidium atom vs. the cesium atom vs. the hydrogen atom but rather on particular technical realizations. They lead, on one end of the scale, to small acceptably performing devices at affordable costs and, on the other end of the spectrum, to very high performing device at substantial sacrifices in size and cost.

Historical developments have indicated² what would happen if we dropped this ranking and attempt to use these existing principles to realize either higher performance as in the case of rubidium or cesium, or lower size and cost as in the case of hydrogen storage. The basic results of these efforts are shown in Figure 2. The Q and, with it, the best frequency stability σ_F can be increased for rubidium and cesium; however, at increased cost and size. The size and cost of a hydrogen device can be decreased; however, at a sacrifice in performance. Furthermore, Figure 3 shows that nearly all of the different atoms have been subjected to the three fundamentally differing basic technologies;^{2,3,4} Beam, storage vessel, and gas cell. In addition, nearly all of the devices have operated as passive resonators serving to stabilize a crystal oscillator or as active oscillators of the maser type. Of special historical interest is the fact that the attempt to interrogate the cesium atom in a storage vessel led to the creation of the hydrogen maser;⁵ a decade later, the idea of pursuing the possibility of a cesium maser led to the passive hydrogen maser principle.^{6,7}

We may conclude from Figure 1 through 3 that there is no fundamental relationship between superior performance nor cost nor size and the particular atom or physical principle which is used, but rather that the combination of expenditure of funds in a historical chain of events is largely responsible for today's device-hierarchy.

Furthermore, it is not a foregone conclusion that very high performance in small size must be created by reducing the size of high performance devices; it may be as well to focus on performance enhancement of devices already small. Therefore, openness of mind is very much in order when judging new ideas and proposals to improve parameters ranging from stability performance to environmental insensitivity to size and cost. It just may be that a truly new idea may change an old principle of a "down-rated" atom into the best solution possible.

IDEAS AND SELECTION CRITERIA

New ideas can fall in the areas of basic research, applied research or engineering. A new idea may be basic, or it may be a solution to an existing or perceived problem, or it could be the revival of a once discontinued or discarded idea. Independent of this classification, there are four basic questions which may be asked and should be answered before resources are expended. By "resources" we mean either an approved program within a government laboratory or the funding of a program in industry or elsewhere.

The following should not lead the reader to believe that some research of an undirected nature should not be approved. Such funding, in the author's belief, is essential, but such resources must be expended in a field of technology or in a field of basic science with proposed results reasonably undefined. Resources spent in this direction have proven over the last few decades (and in fact throughout human history) to be one of the most worthwhile investments.

We now restrict ourselves to proposed ideas for proposed measurable results. They may be subjected to the four questions listed in Figure 4. These questions are aimed at a sequence of logical attack to determine whether the idea is worthwhile to pursue. One word of caution is in order; the author believes that these questions cannot always be unambiguously answered; however, if the answer is clearly a "no" for A or B, and a "yes" for C or D, no resources should be spent. An example from the mid 60's is the thallium beam.⁴ It was pursued as a cure to perceived bad aspects of cesium. As we know today, the thallium beam research was terminated a long time ago and cesium beams are still around. Figure 4 gives the scenario to questions A through D which could have been answered before any expenditure of resources in this particular case in the early 60's.

An idea which is a revival of an old idea is not necessarily bad: the old idea may have been discarded because of limitations of technology at its time, or the revival of the old idea may be worthwhile because other new ideas have created a different scenario. However, there seems to be a set of ideas which appear regularly. These are listed in Figure 5. This is not a complete list but might serve to illustrate further the questions of Figure 4. These ideas remain "new" because the questions listed in Figure 4 have seldom or never been applied to these ideas. The pretense of "new" is no reason in itself to expend resources. The author's favorite is "small size". Question C here is very appropriate; does it introduce a new problem? Using the same physical technology,

reducing the size uniformly lowers the Q. As we have seen from Figures 1 and 2, the Q is linked to the best frequency stability of atomic or crystal clocks. If the very small rubidium cell or the short cesium tube or the small hydrogen bulb lead to reduced Q, it is an illusion to believe that the stability performance of the original full size device can be retained.

Figure 6 shows the history of passive hydrogen development. This is an interesting example involving the author in a very intimate way. In 1969, at the National Bureau of Standards, D. Halford asked the author about the pro's and con's of adapting the maser principle to the cesium beam. The resulting analysis took several months of fruitful discussion and led to the idea of the passive hydrogen resonator device: the limitations of the hydrogen maser in long-term were cavity pulling; this effect was highly reduced in a passively operating device, especially if particle interrogation was used.⁷ The author then experimented with the hydrogen storage beam but ran, as did the pure beam⁹ work of H. Peters at NASA, into problems which were related to the difficulties of efficiently detecting hydrogen atoms. Thus, the future of the hydrogen storage beam is critically dependent on the availability of efficient hydrogen detectors. There still are no efficient hydrogen detectors. However, as soon as this changes, a discarded old idea may become a worthwhile new idea (Ref. Figures 4 and 5).

The author's solution to the detection problem was the concept of the passive hydrogen maser⁸ which does not fully realize the advantage one obtains in cavity pulling (or lack of it) by detecting particles but retains the advantage of a passive device over an active device in this regard. Pioneering work in the electronic design and further refinement of the concept by F. Walls at NBS then lead to experimental realizations of the low cavity-Q, small, passive hydrogen maser and the full size, passive hydrogen maser.¹⁰ These concepts now have lead to several government-funded pursuits of realizations of the passive hydrogen concept¹¹ which include the novel-cavity-mode-small-maser, the dielectric-cavity-small-maser, and the positive-feedback-small-active-maser (a combination of the small, passive maser idea with an old idea realized previously in hydrogen).¹² Thus, the time and frequency community is now dealing with a family of six, somewhat different solutions using the passive hydrogen principle and the expenditure of many millions of dollars with some of the questions previously addressed not asked or answered in full.

THE PROBLEM OF TRANSFER TO INDUSTRY

Transfer to industry for the purpose of commercial or government-need-oriented production appears to be the ultimate goal of most government funded efforts. In fact, most researchers and engineers will agree that a successful transfer to industry would be the ultimate goal of their agencies as well as an important ingredient in their personal and professional motivation. This question can be addressed from various angles. The first is depicted in Figure 7 which illustrates the role of the clock expert. The clock expert is typically an individual with privileged knowledge or background or experience in relation to what is important in clocks. Thus, the clock expert can be characterized as having special knowledge in connection with the physics package (crystal resonator, rubidium optical package, cesium beam tube or hydrogen maser) and with the problems of testing, measuring and characterizing the complete system. Frequently the clock expert also plays an important role in the interface between the physics package and the electronics system of the clock or frequency standard.

In Figure 8 we list organizational modes and probable results. Like all other technology, the making of clocks and frequency standards involves engineering, quality assurance, manufacturing and testing. If an organization has these four functions, such as they are present in most industries, we have the potential of manufacturing; however, due to the complexity of crystal and atomic clocks, the absence of a clock expert may lead to the manufacture of clocks which are beset by fundamental problems. If a clock expert is inserted into the clock making process directly contributing to the creation of hardware, the clock expert will mostly be found in either or both of the following: engineering and testing (based on the specialties of the clock expert as shown in Figure 7). In this role, the clock expert can assure that working clocks are produced but the links to quality assurance and manufacturing are not properly established; thus, there is the potential of working clocks, but only one at a time, plus potential shortcomings in reliability and serviceability. In government laboratories which are not oriented towards manufacturing, quality assurance and manufacturing as operational entities typically do not exist; thus, this example also characterizes government laboratories: They can reach out and produce prototype devices but cannot actually produce clocks. The desirable and ideal situation is approached by the third part of Figure 8 where the clock expert is placed within management or in a technical/consulting role focussing not only on the four parts of the manufacturing process but on the interfaces between these four processes. Such an organization offers the potential of making not only good working clocks, but producing these clocks in quantity with reliability.

We are now ready to answer the question: When is the best timing for transfer from government to industry? An attempt to give an answer is Figure 9. The figure depicts the sequence from the original idea to production in seven steps: The idea, the experimental verification of the idea, demonstrating feasibility in a laboratory or bread-board setting, the demonstration model which does not have size, weight or power constraints but shows all aspects of performance, the engineering development model (EDM), the pre-production model (PPM) and the production. Since industry contributes original ideas as well, we list this as an alternate idea-start. The idea is carried through experimental verification and the demonstration of feasibility. At this point the critical timing for transfer from government to industry arises. The reason for this lies in the results discussed in Figures 7 and 8. At this point, the full circle of a manufacturing operation comes into focus: Engineering, Quality Assurance, Testing and Manufacturing become a planned process, displaying a high degree of coherence which is phased in time. If government work progresses beyond this stage; i.e., through the demonstration model, or even to the EDM or PPM phase, this work becomes increasingly alien to the coherence of the industrial manufacturing process. In other words, resources spent, in a government laboratory, beyond the stage of demonstrating feasibility are probably wasted because industry will not be able to take advantage of it because aspects of quality assurance, producibility, cost, etc. are not properly accounted for.

The issue in relation to Figure 9 is not that of funding per se; we assume that funding is available and can be channelled at the right time in the right direction. The problem, rather, is that a misunderstanding may persist: As viewed from the government side, it appears that the government has spent significant resources and has come up with an almost producible clock or frequency standard; in contrast, industry must request substantial additional resources to go "back to the drawing board" for reasons of quality assurance, reliability, producibility, etc. To the government this looks like unnecessary duplication, to industry it looks like an unacceptable constraint. Therefore, we have the phenomena of reluctance to fund such work on the government side, reluctance to accept such work from the industry side in addition to issues of professionalism and recognition of contributions. Recognition of the critical timing for transfer is the more important, if one realizes that the majority of funds are expended after the demonstration of feasibility with the consequence of increased irreversibility of the process once carried too far.

CONSTRAINTS OF INDUSTRY

History has taught us that clock and frequency standard development, because of the complexity and state-of-the-art nature of the devices, may span many years or even a decade from idea to production. Industry has several concerns in the process of accepting, counter-proposing, or even rejecting government-funded work. A most serious and often overlooked aspect is the engineering content versus the manufacturing content of government-funded work. Figure 10 is an attempt to depict this predicament. Plotted is the effort level (funding level) as a function of time. The pre-EDM phase includes all stages from idea to demonstrating feasibility including the demonstration model. The effort level is comparatively low and calls almost exclusively on the research and engineering talent of the organization. The effort level is substantially increased (up to a factor of ten) but retains its largely engineering content with the engineering development model. It is important to highlight this jump in effort level because this often-overlooked fact a-priori rules out that all (even worthwhile) pre-EDM efforts can reach production maturity. There simply are not enough resources available for product realization of all good ideas. For example, the National Bureau of Standards frequency standards effort operates at about the million dollar level. If all of the ideas and concepts developed there would meet all of our criteria and lead to full scale industrial efforts, the required funding level is about ten times higher. That means we would have to have resources at approximately the 10 million dollar per year level just to execute all of the NBS ideas in industry and NBS is only one of several such laboratories.

After the EDM stage, the first significant change of effort-mix occurs: Manufacturing begins, causing a drop in the engineering content of the total effort level while the total effort level continues. The PPM stage is followed by the production stage which may be at the same level, at a higher or lower level depending on the value of the product and the rate of production. Important is the fact that the total effort level remains substantial while the engineering content is reduced to a very small level serving only as production support and trouble shooting. This fact puts industry in a predicament; as shown in Figure 10, a substantial team of engineers and scientists is needed to execute the EDM and the following PPM phase but only few basic resources are required before and after this phase.

How shall industry gear-up its engineering staff from the pre-EDM phase to the EDM and PPM phase and what should this staff do after production has started? The hard-nosed answer to this is to hire and then reduce staff again. It is the author's belief that clock efforts which are based on a quick hiring process with the potential of substantial re-orientation or loss-of-job after a relatively short time will not lead to success in the complex challenges of clock making. Thus it is incumbent upon the government to insure continuity in those efforts which exist solely because of a government mandate. Continuity can be provided by successive upgrading of the product through consecutive EDM and PPM phases time-phased with production of the previous product. Another alternative is funding of related or complementary efforts after the engineering and pre-production of the main product have been consumed.

CONCLUSIONS

In the decision making process on a new product, many thoughts and conditions have to be considered. Figure 11 depicts what may be called the decision tree for product development. This decision tree starts with an idea; this idea may come from government or from industry in the form of a proposal or a request for a proposal. Industry will first analyze this for basic validity as a solution to an existing problem or validity as a new product or capability. The first steps are the considerations on performance improvement and degradation (comp. Figure 4). If the answer to the first question is no, there will be no further consideration. If the answer to the second question is yes there still may be a valid idea if the performance degradation is acceptable. The next step is an analysis of the engineering costs; are they acceptable? With engineering costs it is not only the amount of monetary resources at stake, but also the question of human resources as discussed above; also, one must ask whether the needed engineers could produce other things of higher value than the one in question (concept of foregone benefits). If the answer is 'no', government funding must be available to offset the costs of engineering. These costs, of course, relate to the market size in the sense of return on investment. If the market size is unacceptable, the government may be the sole customer and must bear the product funding as well. Manufacturing industry will be, in general, reluctant to pursue an engineering development effort with no prospect for production. If government funding is available and/or the engineering costs are acceptable, and/or the market size is acceptable, the required capital equipment investment is analyzed. If the work is government-funded, invariably the need

for government funds for capital investment arises. Substantial capital investment needs must be offset by government furnished equipment or the funding of equipment purchases which then become property of the government.

Finally, the question whether the targeted product competes with the present product line of the company must be addressed. There will be general reluctance to develop and create a product if such a product competes within the existing market and does not serve to enlarge the market expansion. Other considerations, however, may enter here; thus the decision on this question is not clear-cut. However, a go-ahead is almost universally given if the new product opens new markets adding to sales and enhancing capabilities.

It appears proper to conclude with some thoughts about reliability. It is self-evident, that reliability is probably the most important issue in clock technology because of the very nature of the clocks principal function: time-keeping. Reliability must have proper attention in the engineering phase (reliability engineering), it must be addressed with high priority in the manufacturing process (quality control and quality assurance), but, most importantly, it must benefit from field-feedback. This latter element requires long-term continuity of the clock development, production and application scenario, which is characterized by stability of the organizations involved, by business commitments between government and industry, and by maximizing quantities of products while minimizing engineering changes outside of performance or reliability mandated actions.

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	QUARTZ CRYSTAL RESONATOR	RUBIDIUM GAS CELL	CESIUM BEAM	ATOMIC HYDROGEN STORAGE BULB
TYPICAL Q	2×10^6	2×10^7	3×10^7	1×10^9
TYPICAL σ_F	1×10^{-12}	3×10^{-13}	5×10^{-14}	3×10^{-15}
SIZE & COST (CM ³)	SMALL (10 ³)	MEDIUM (10 ³ -10 ⁴)	LARGE (10 ⁴)	ENORMOUS (10 ⁵ -10 ⁶)

THE CLOCK HIERARCHY

FIGURE 1

	QUARTZ CRYSTAL RESONATOR	RUBIDIUM GAS CELL	CESIUM BEAM	ATOMIC HYDROGEN STORAGE BULB
REALIZATION	NOT YET TRIED	MASER	PRIMARY STANDARD	SMALL PASSIVE MASER
σ_F	—	10^{-14}	10^{-14}	10^{-14}
Q	—	SOME 10^8	SOME 10^8	SOME 10^8

CLOCK HIERARCHY
(SIZE/COST EQUALIZED)

FIGURE 2

	BEAM	STORAGE VESSEL	GAS CELL	PASSIVE	ACTIVE
H	YES	YES	NO	YES	YES
Rb	YES	YES	YES	YES	YES
Cs	YES	(1)	YES	YES	(2)
ATOM X	YES	YES	YES	YES	YES

(1) THIS IDEA CREATED THE ACTIVE H-MASER

(2) THIS IDEA CREATED THE PASSIVE H-MASER

MATRIX OF CLOCK PRINCIPLES

FIGURE 3

- (A) DOES IT REMOVE A LIMITATION?
- (B) IS THIS LIMITATION A REAL PROBLEM?
- (C) DOES IT INTRODUCE A NEW PROBLEM?
- (D) IS THIS NEW PROBLEM A REAL LIMITATION?

EXAMPLE: THALLIUM BEAM (vs. CESIUM)

- (A) YES, MAGNETIC SENSITIVITY MUCH LESS.
- (B) NO, SINCE SHIELDING OF CESIUM IS ADEQUATE.
- (C) YES, LESS BEAM DEFLECTION; SURFACE IONIZATION NOT EFFICIENT, HIGH OVEN TEMP.
- (D) YES, TECHNICAL SIMPLICITY OF CESIUM MUST BE GIVEN UP.

NEW IDEA CHECKLIST

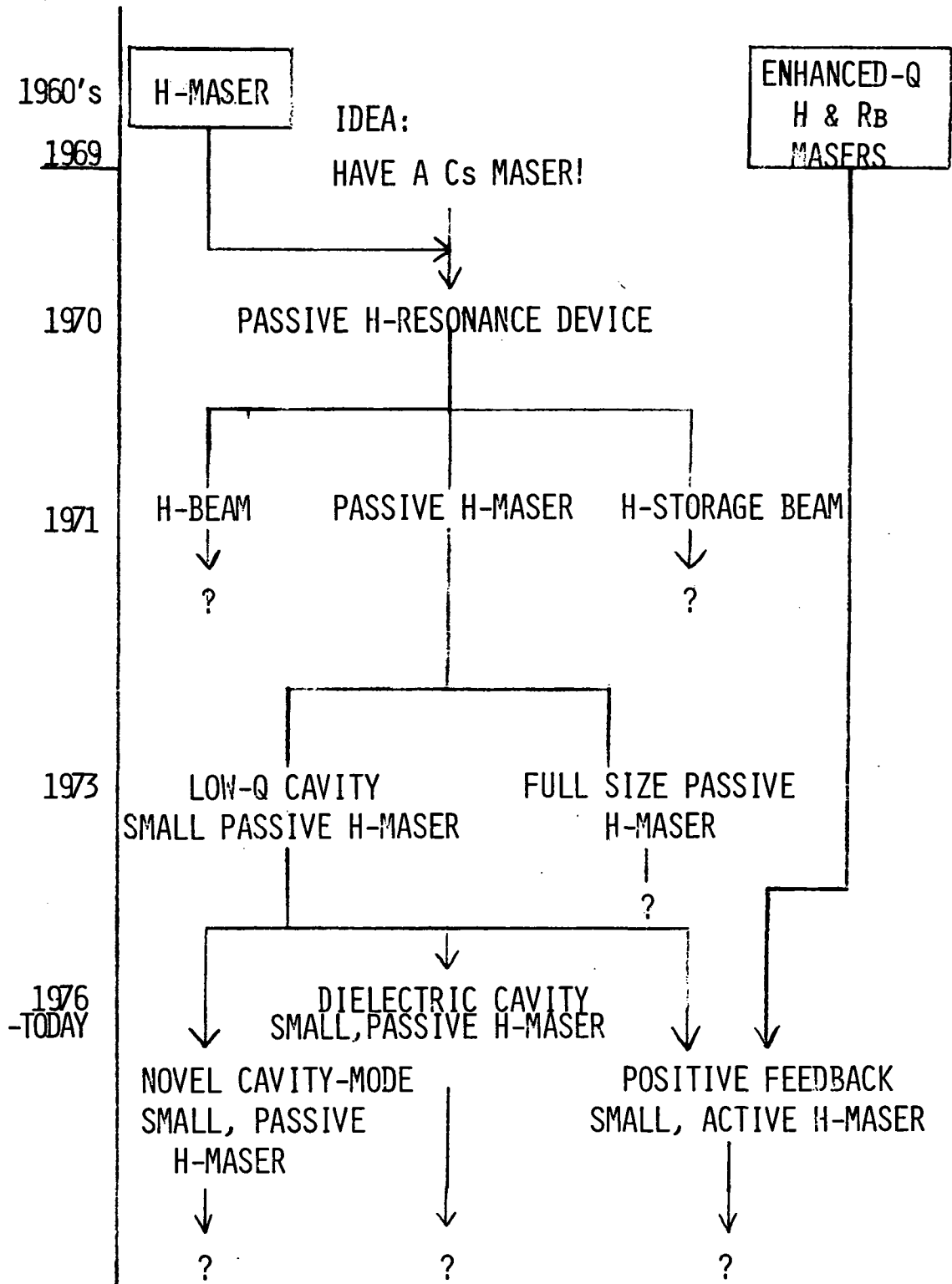
FIGURE 4

- INCREASE CAVITY - Q
- DECREASE CAVITY - Q
- RABI CAVITY
- USE A DIFFERENT ATOM
- MORE OVENS
- LESS OVENS
- MORE SERVOS
- LESS SERVOS
- SYNTHESIZERS IN THE SECONDARY LOOP
- SMALL SIZE

PLUS MANY MORE

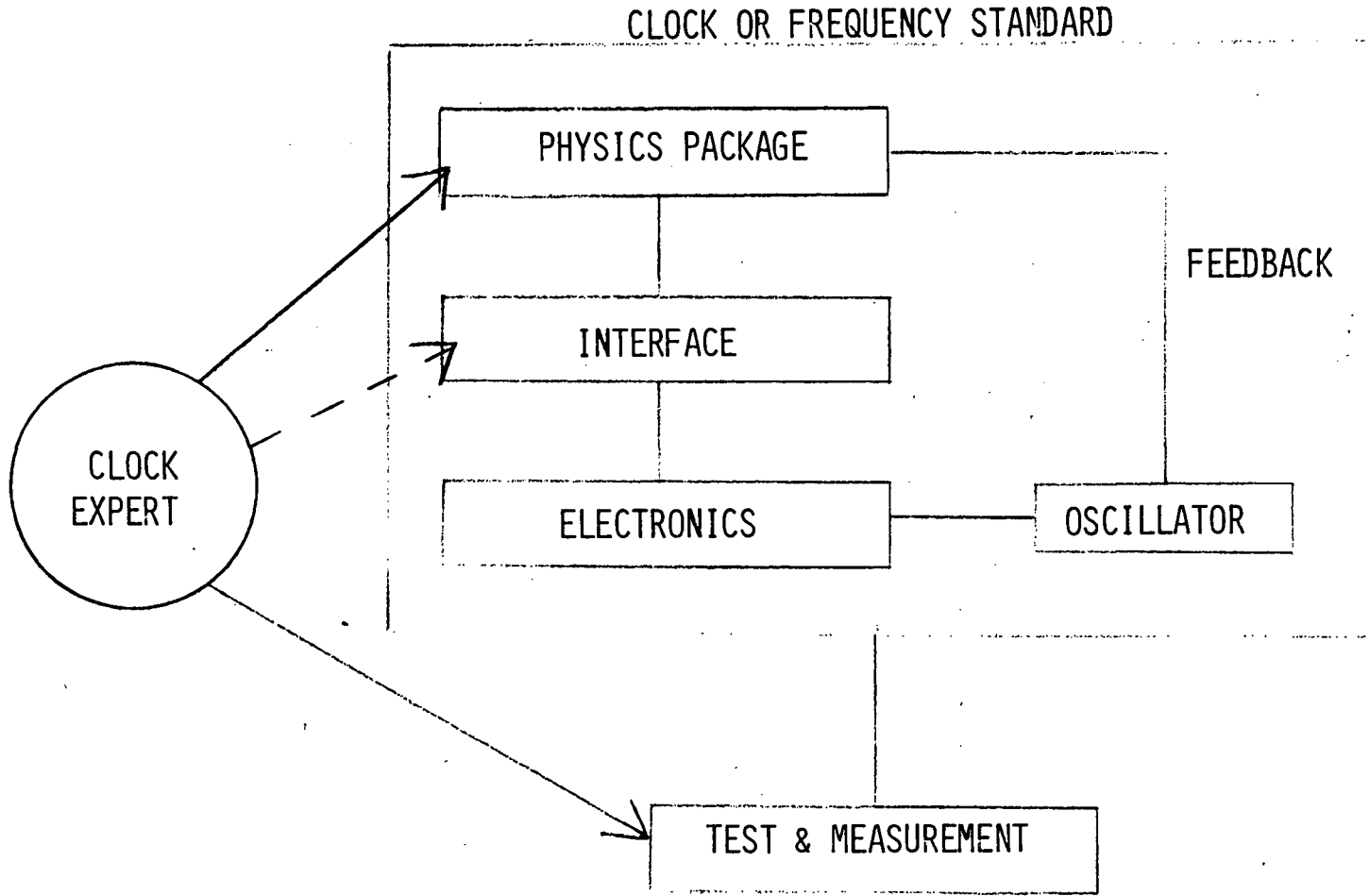
PERENNIAL "NEW" IDEAS

FIGURE 5



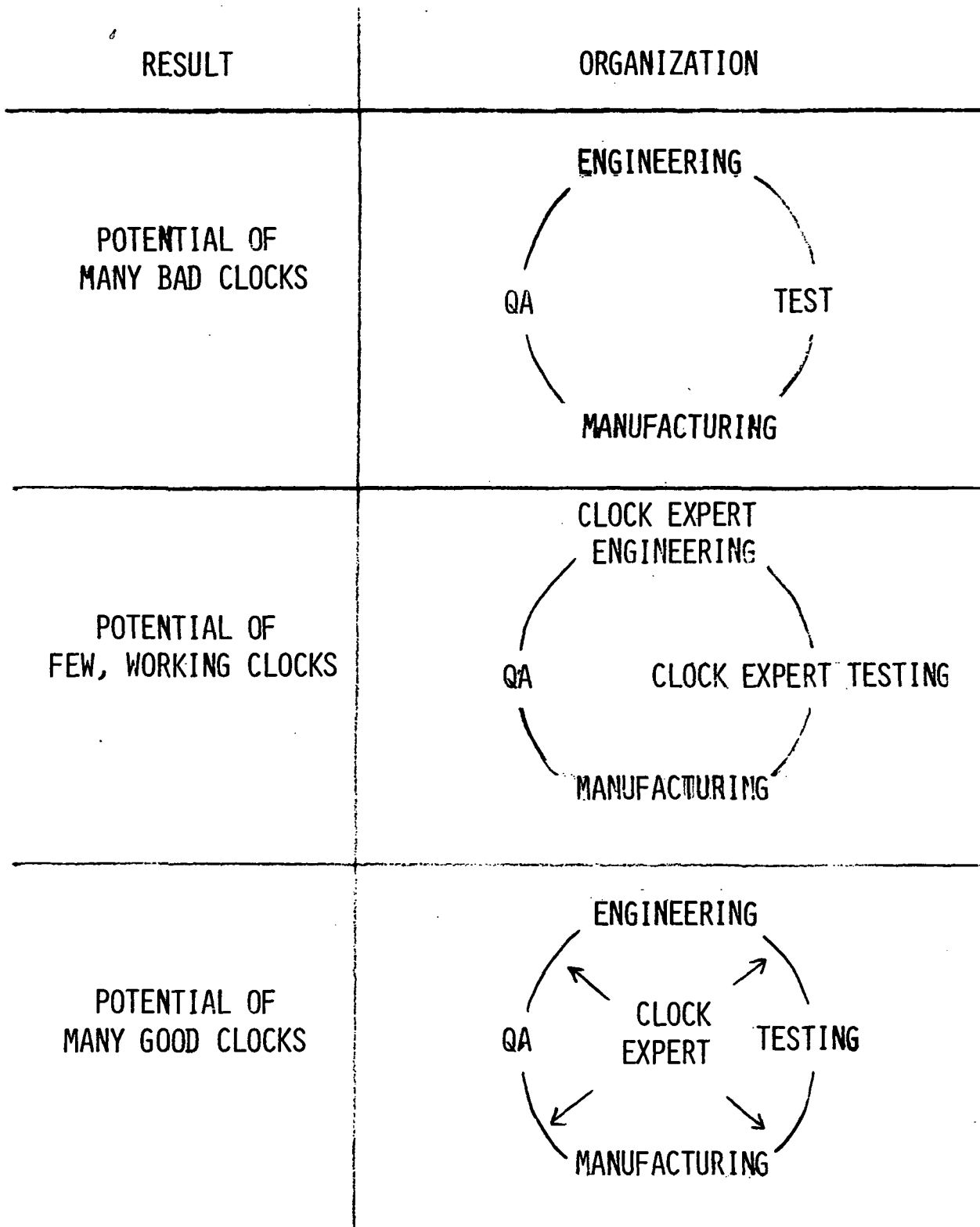
PASSIVE H-MASER FAMILY TREE

FIGURE 6



TYPICAL CLOCK-EXPERT EXPERTISE

FIGURE 7



CLOCK PRODUCTION ASPECTS

FIGURE 8

	IDEA	EXPERIMENTAL VERIFICATION	DEMONSTRATING FEASIBILITY	DEMONSTRATION MODEL	EDM	PPM	PRODUCTION
GOVERNMENT	✓	✓	✓	(✓)	(✓)	(✓)	—
INDUSTRY	(✓)	(✓)	(✓)	✓	✓	✓	✓

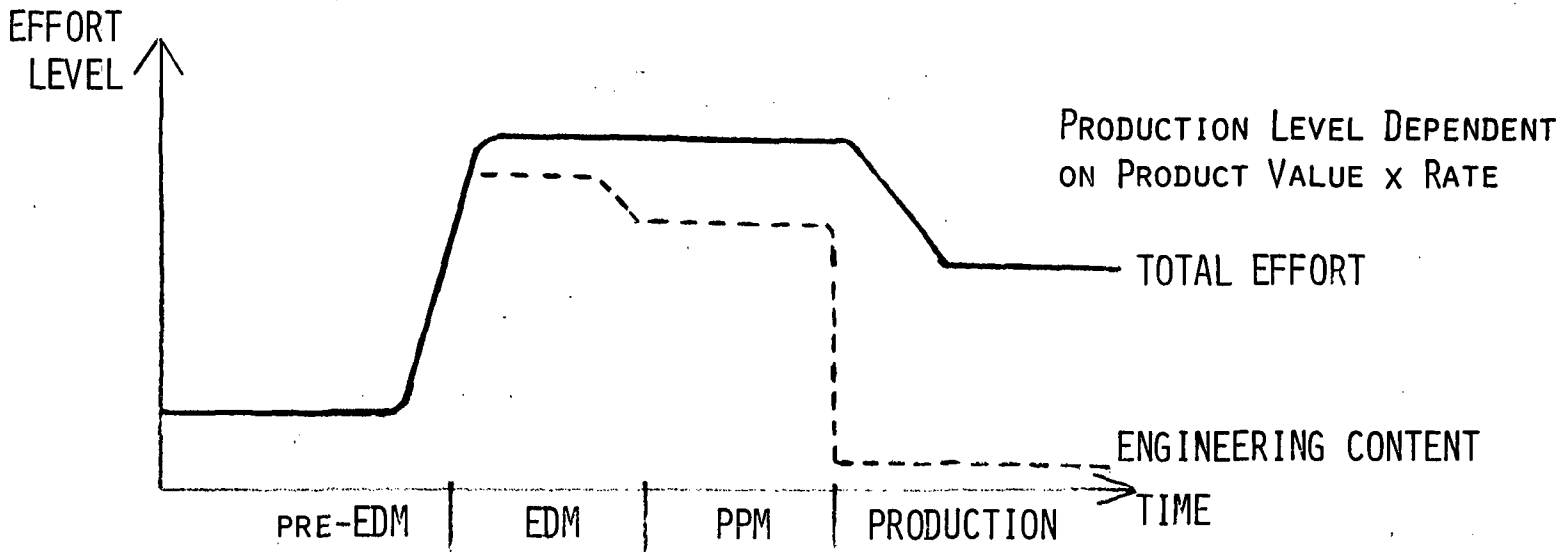
NOTE
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() = POSSIBLE INVOLVEMENT

NOTE: CRITICAL TIMING FOR TRANSFER

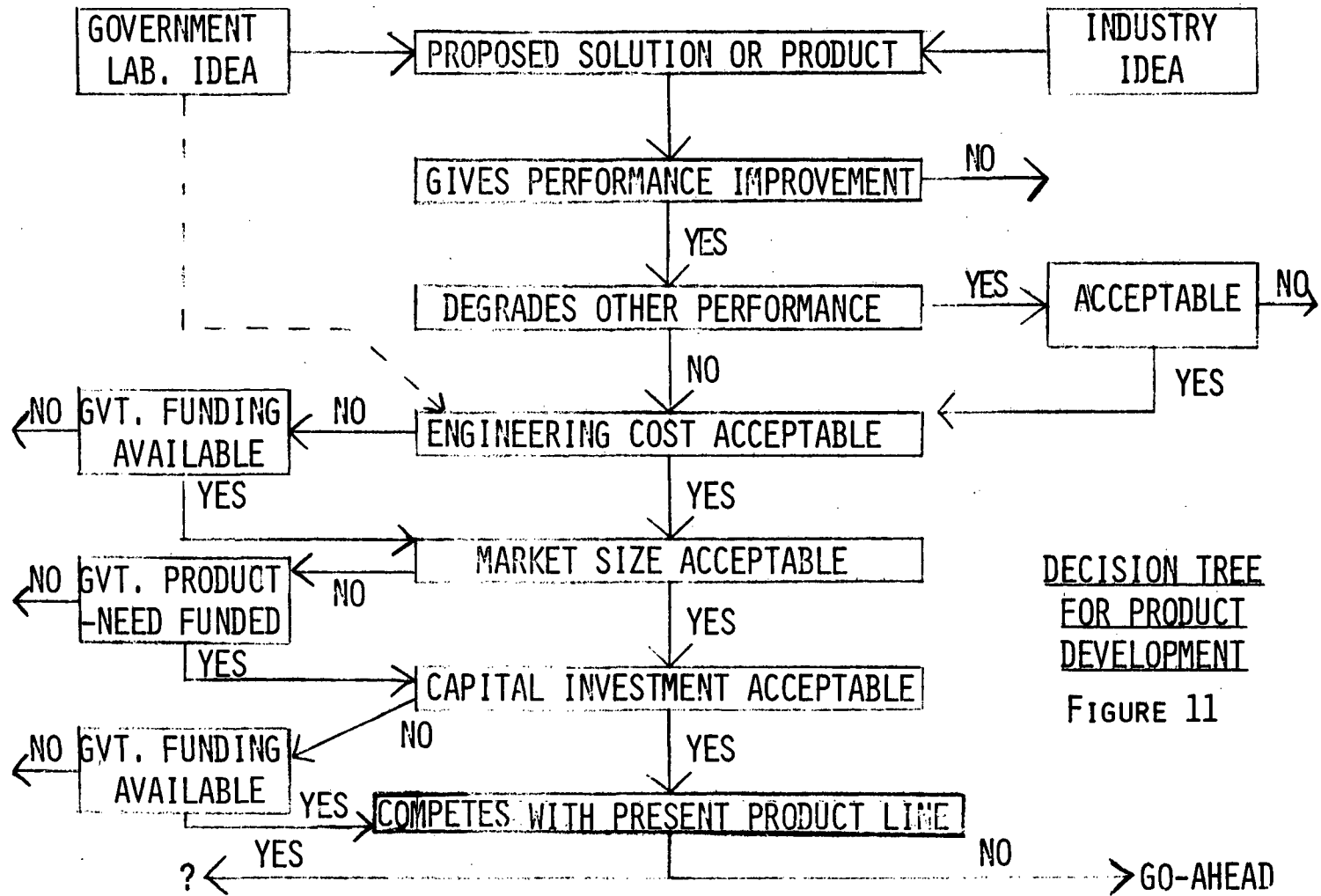
TECHNOLOGY TRANSFER

FIGURE 9



TOTAL AND ENGINEERING EFFORT-LEVEL

FIGURE 10



DECISION TREE FOR PRODUCT DEVELOPMENT
FIGURE 11

FIGURE 11

QUESTIONS AND ANSWERS

DR. WINKLER:

I think your excellent speech has focused on many interesting aspects; two of which are particularly important. The first one, the danger of a government laboratory trying to produce a product in mass production. I have several examples of that mistake, I am deeply concerned about it and I don't know what to do to convince the various incumbents that it is a major mistake.

It is not only contrary to our national policy to keep government out of production as much as possible (beyond the feasibility models and technology studies) but it is also a major mistake for the laboratory to absorb your creative engineering potential solving production problems. Your most precious human resource could be put much better to use on new studies, advanced concepts, and specifications, which I think are the most difficult things in the world.

Now, the second point, is that you have a bewildering array of combinations of beam lasers and active and passive and greater Q and less Q -- kind of reminds me of a very similar discussion which we had about six years ago. I hope you don't remember it.

DR. HELLWIG:

Because I will give the same example. Here in America since our major industrial achievement is the automobile, there is no better example than the automobile. There are certain engineering combinations which can be played upon. You can have the engine in front with rear-drive, engine in front with front-drive, engine in rear with rear-drive, but one that has never been tried is the engine in rear with front-drive.

In automatically controlled oscillators, all combinations have been tried, however.